Hunting for Dark Matter @ Colliders

SUSY 2011

(Hey, can we call this conference something different next year?)

Roni Harnik, Fermilab

Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - in progress

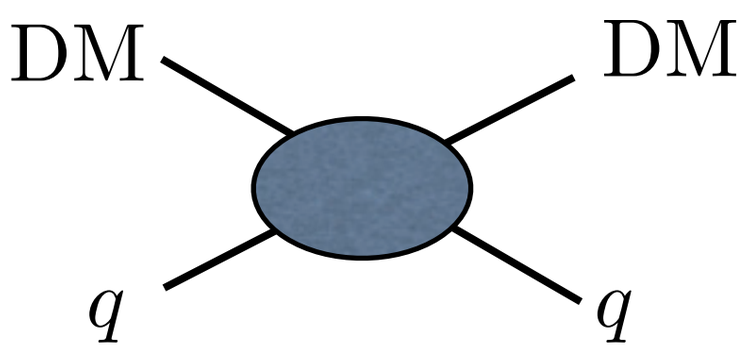
see talk by Tim on Wed.

Very related work by the "Irvine Clan":
Goodman, Ibe, Rajaraman, Shepard, Tait and Haibo Yu -1005.1286
Goodman, Ibe, Rajaraman, Shepard, Tait and Haibo Yu - 1008.1783
Fortin and Tait - 1103.3289
Rajaraman, Shepard,Tait and Wijangco - 1108.1196

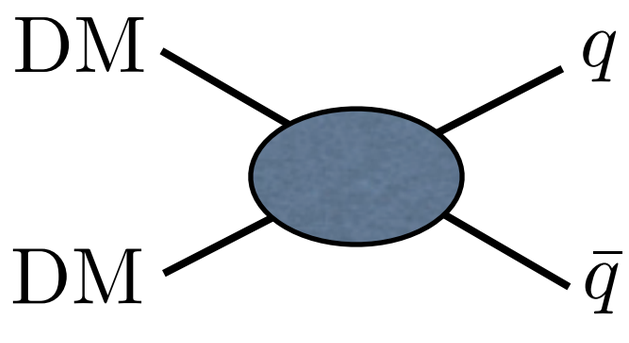
Probes of DM Interactions

* We hope to probe dark matter in several ways:

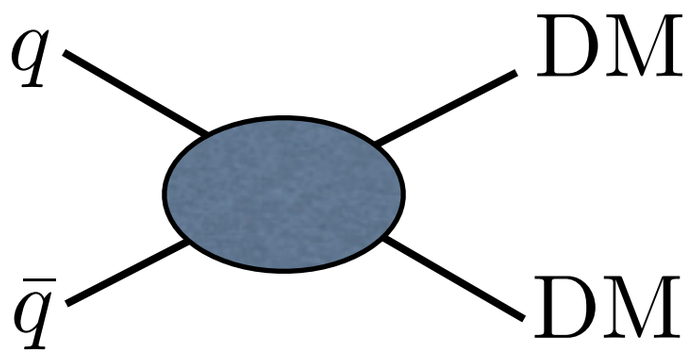
DM-nucleus scattering



DM annihilation

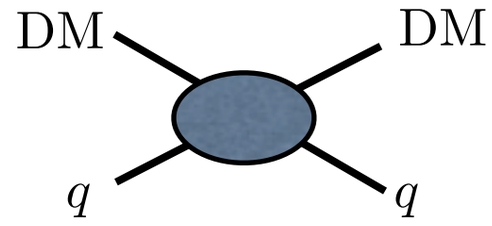


* This talk will relate this blob to DM production at a collider *as directly and model independently as possible:*

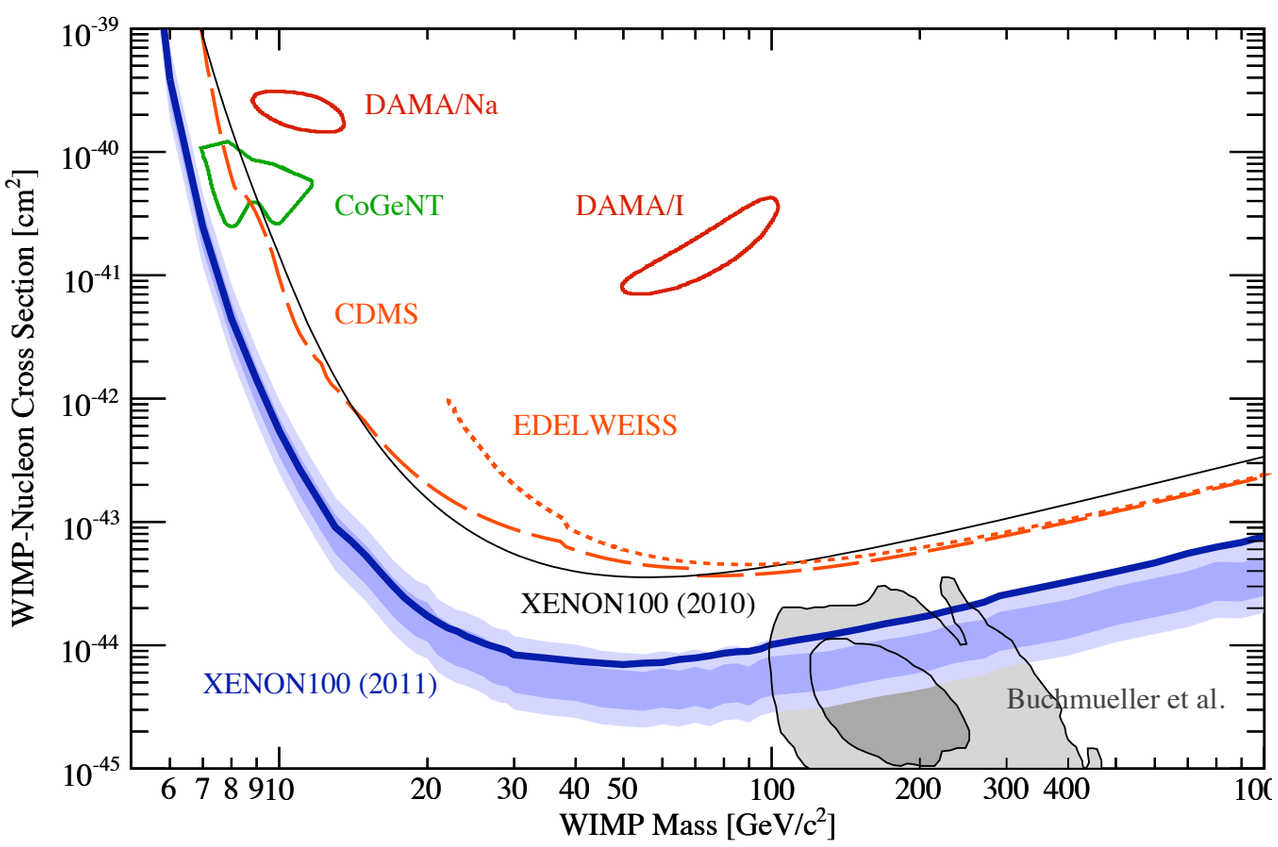


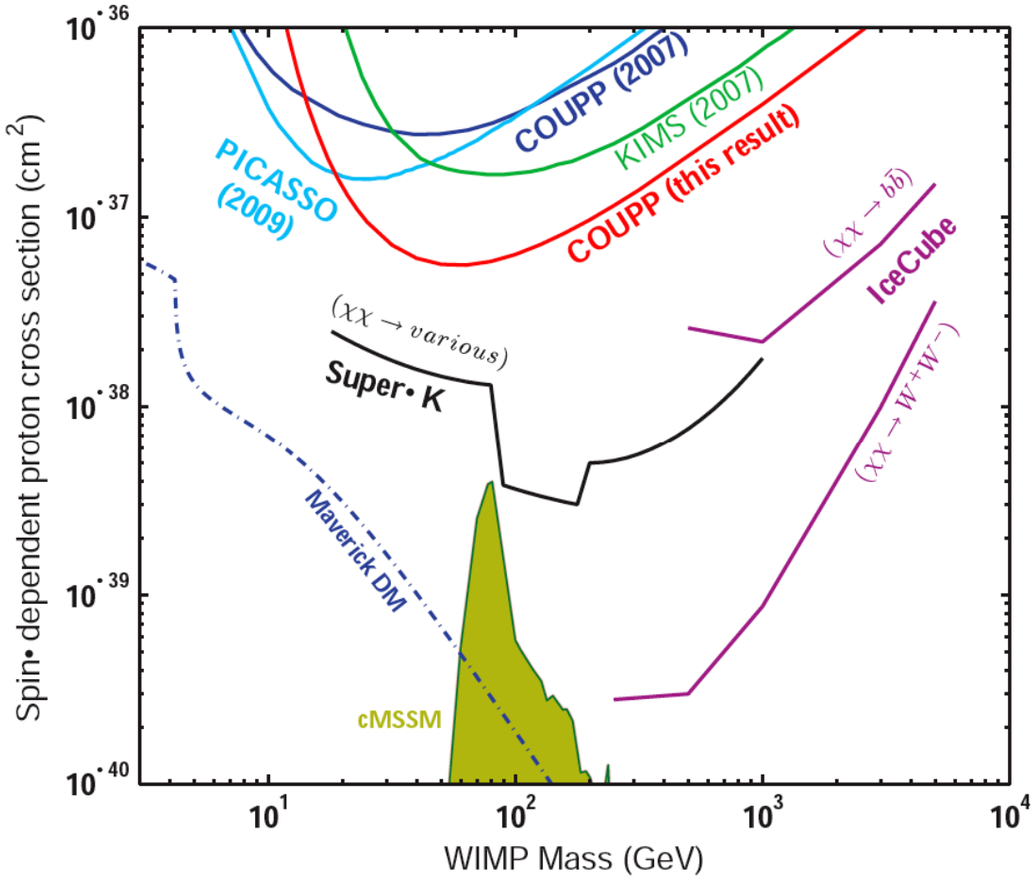
(Focus on direct detection in this talk. similar games can be played for indirect)

Direct Detection

* Direct detection places limits on 

.
* Heroic effort with remarkable results.
* DD has some weaknesses.





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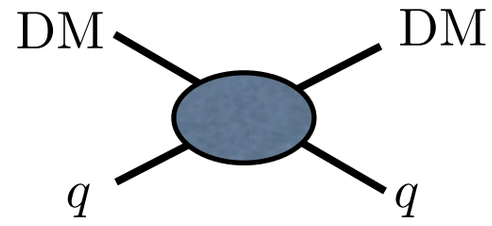
* Direct detection places limits on 

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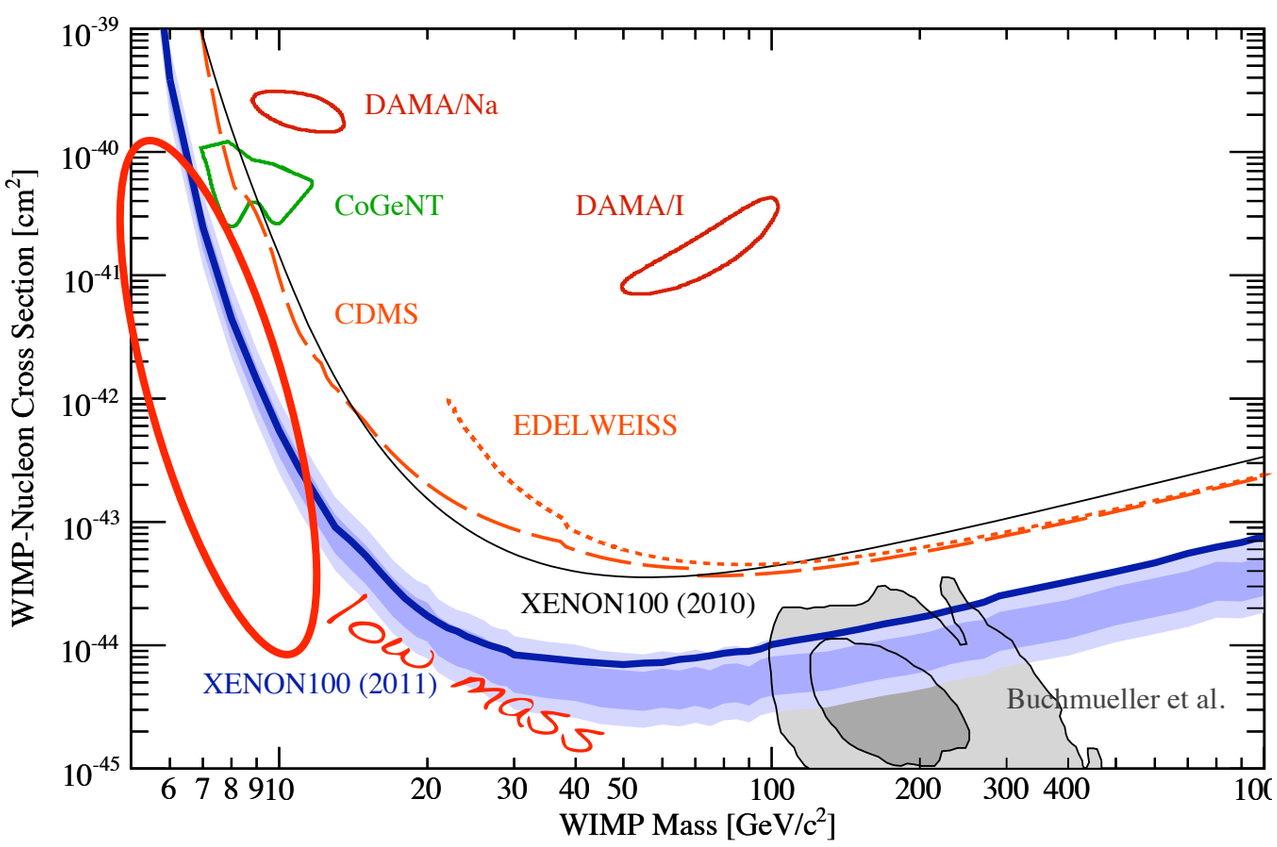

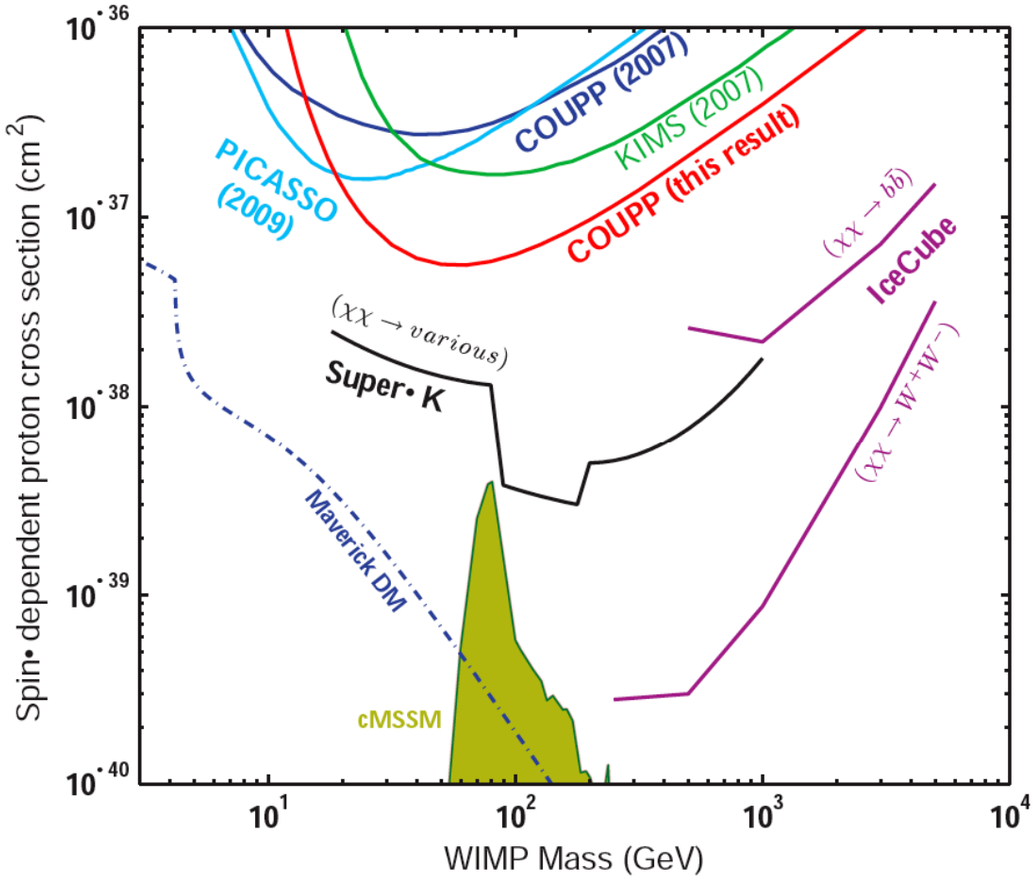

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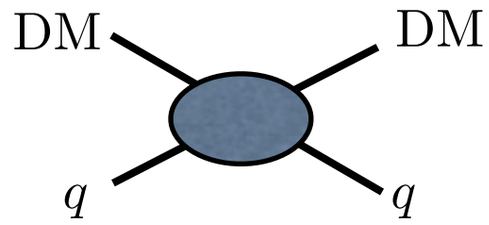
* Direct detection places limits on 

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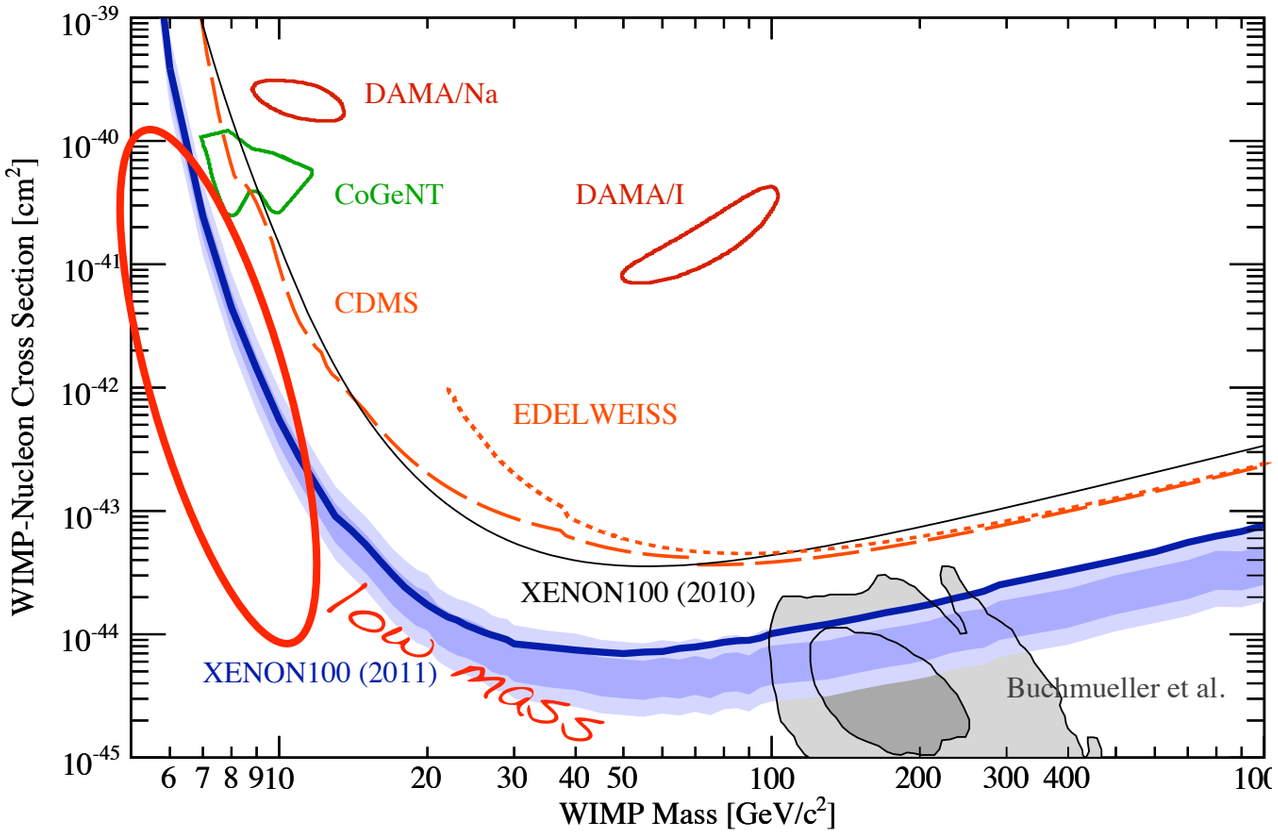
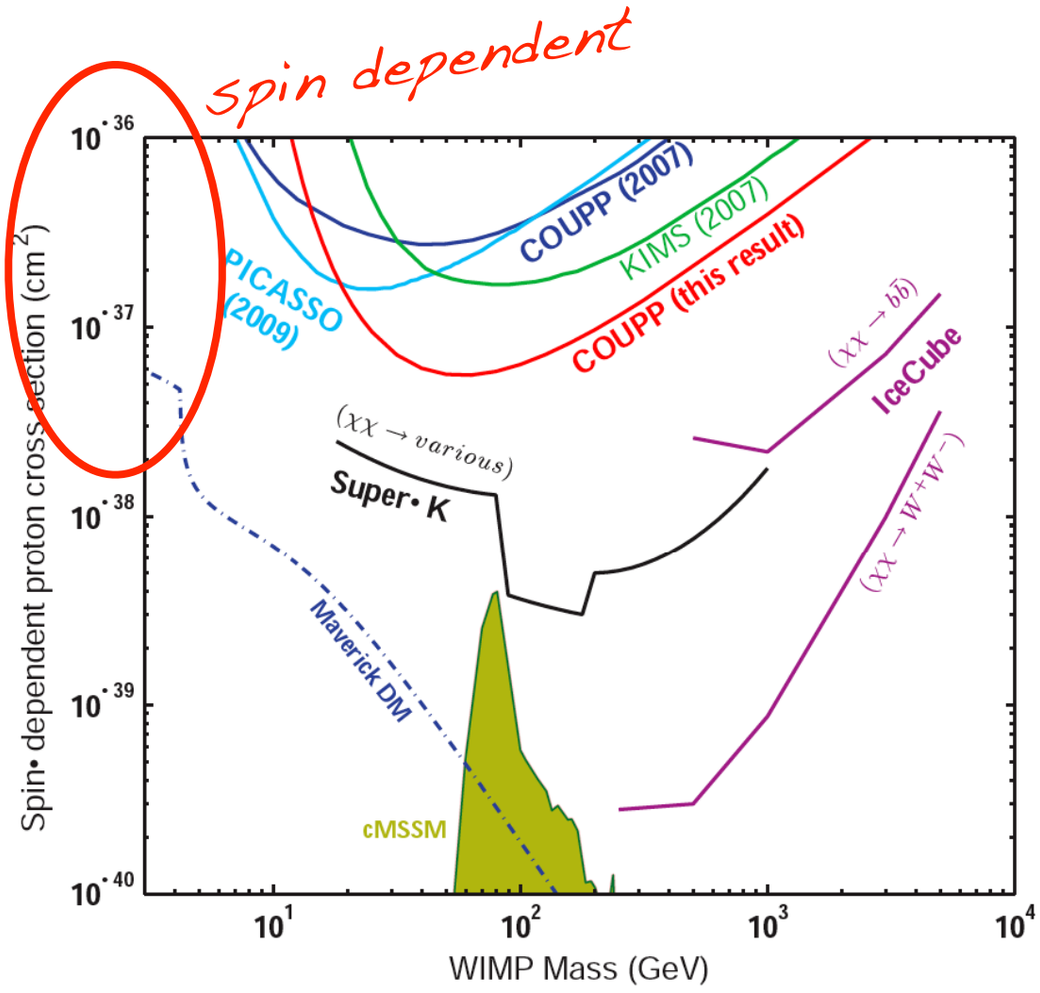
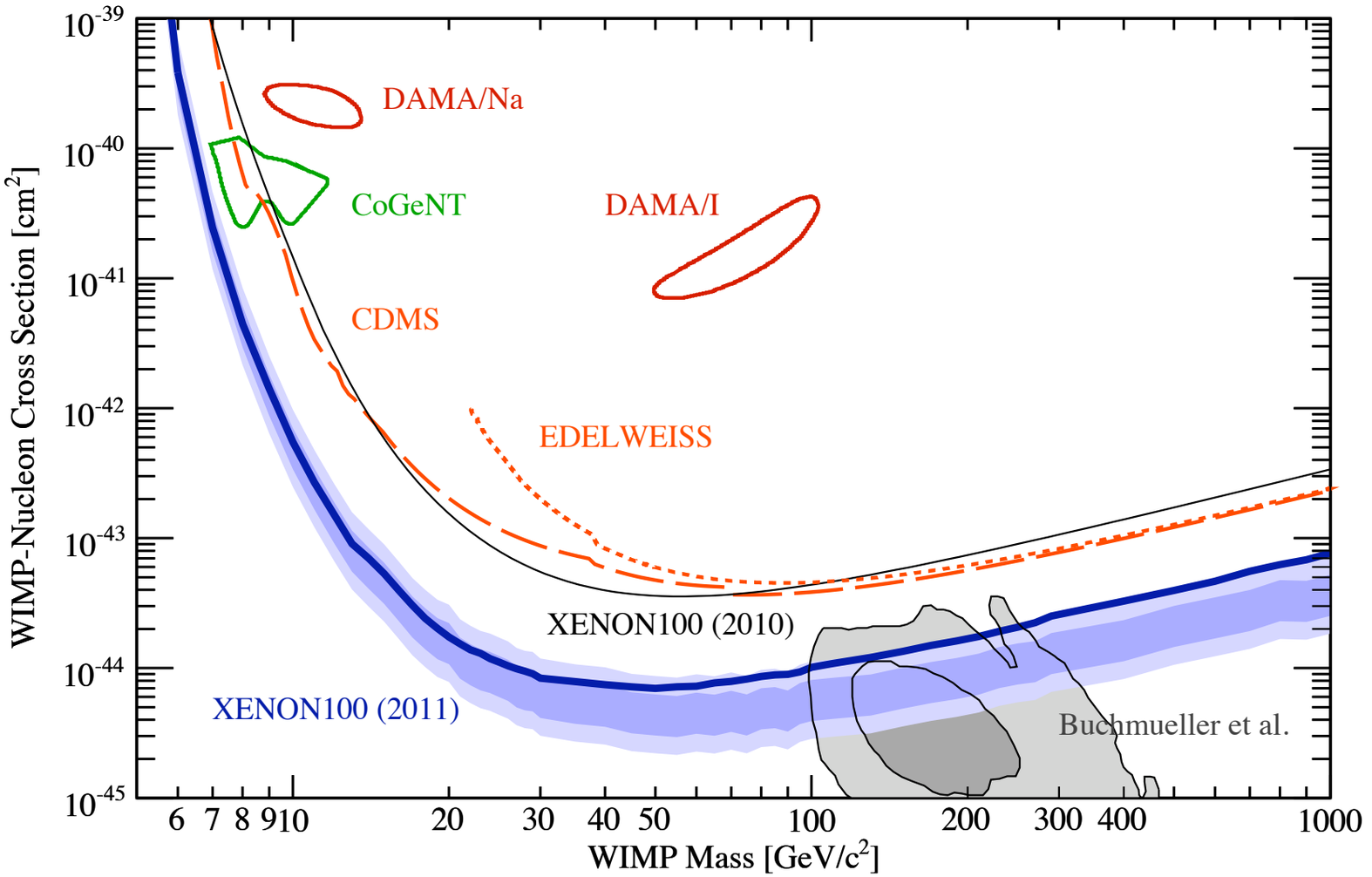




Collider Connections?

* DM experiments and colliders are often said to be related in a specific framework (which happens to have a conference named after it) and certain priors. If theorists work hard...



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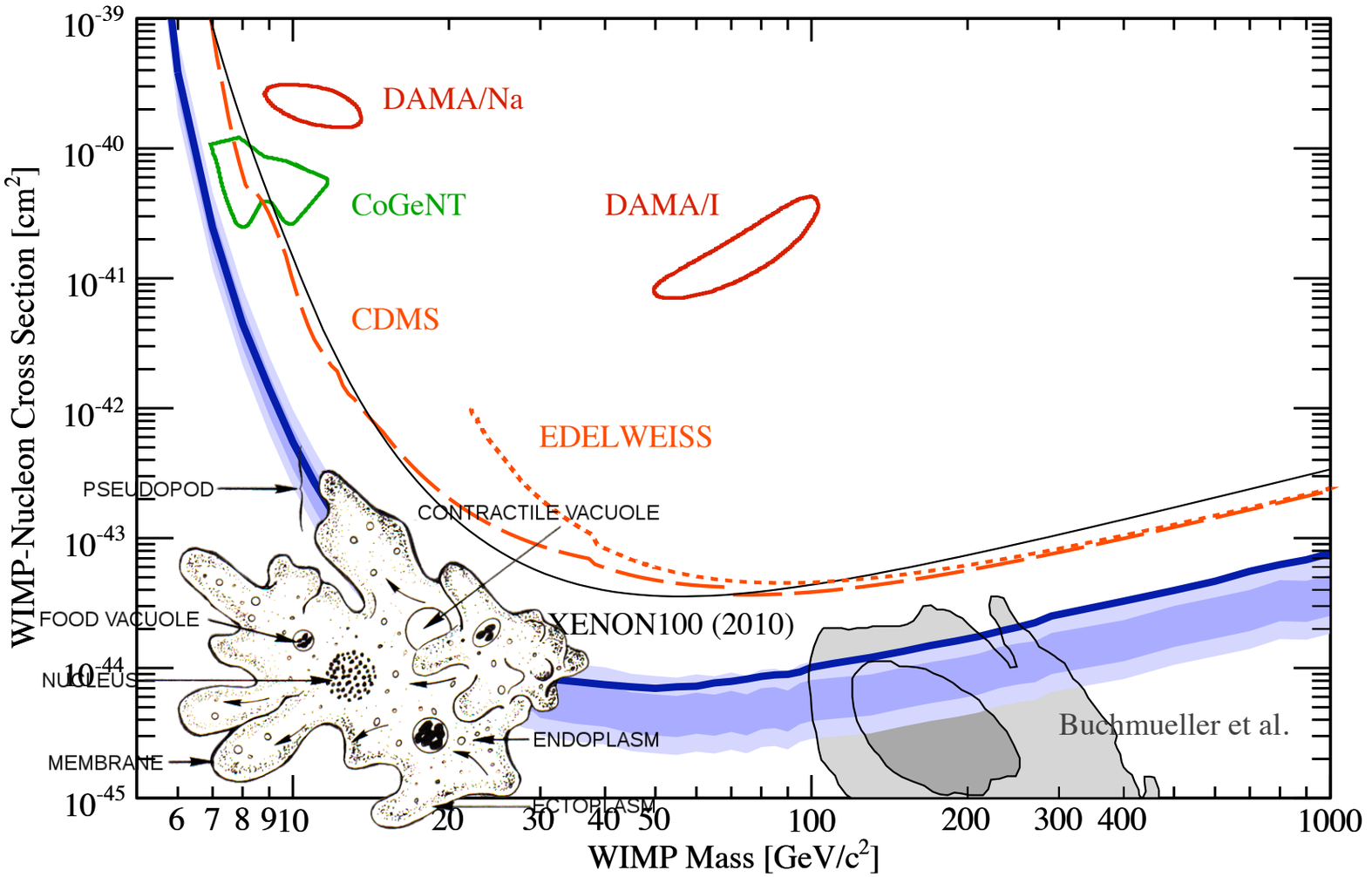

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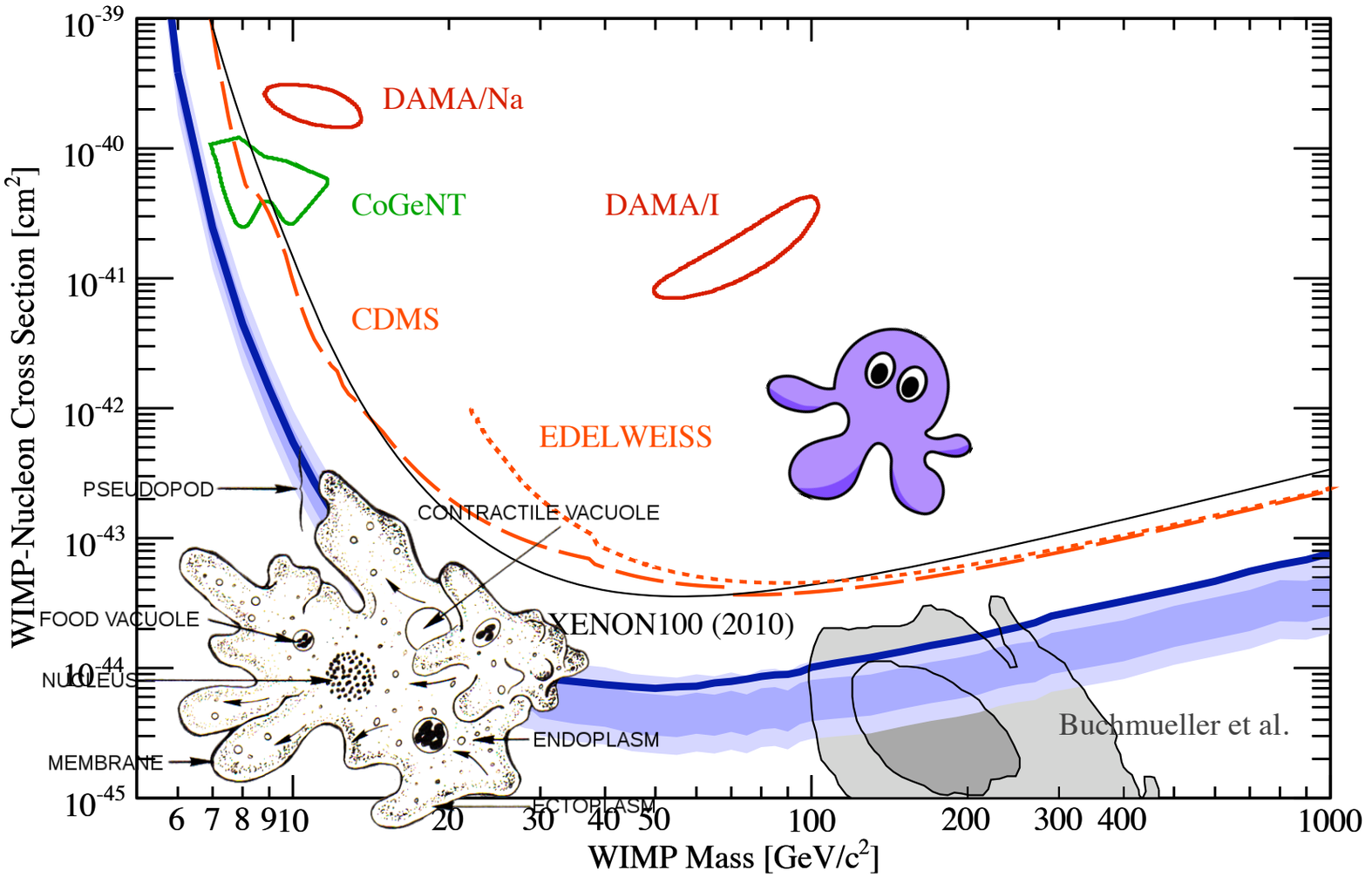

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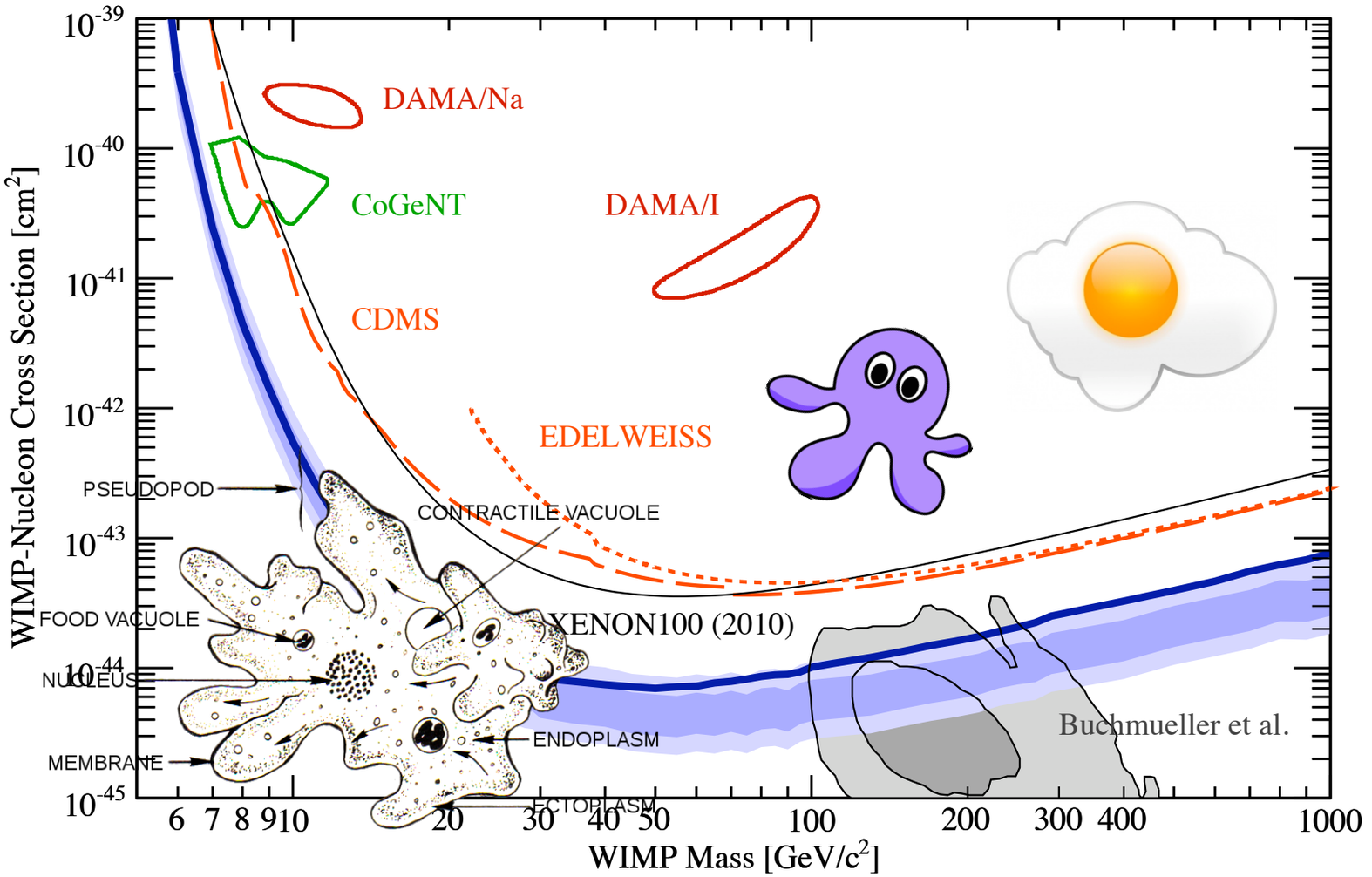

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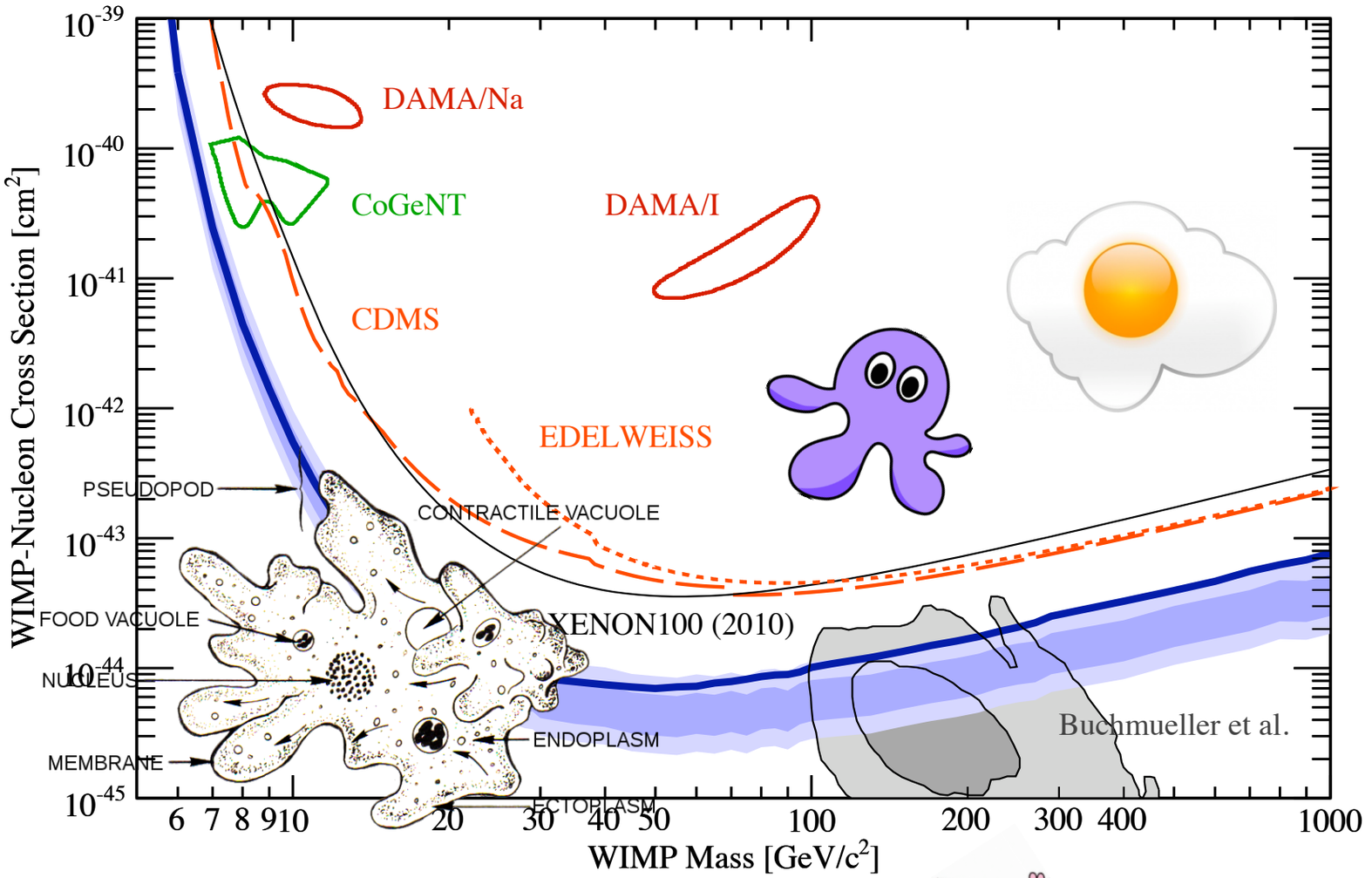

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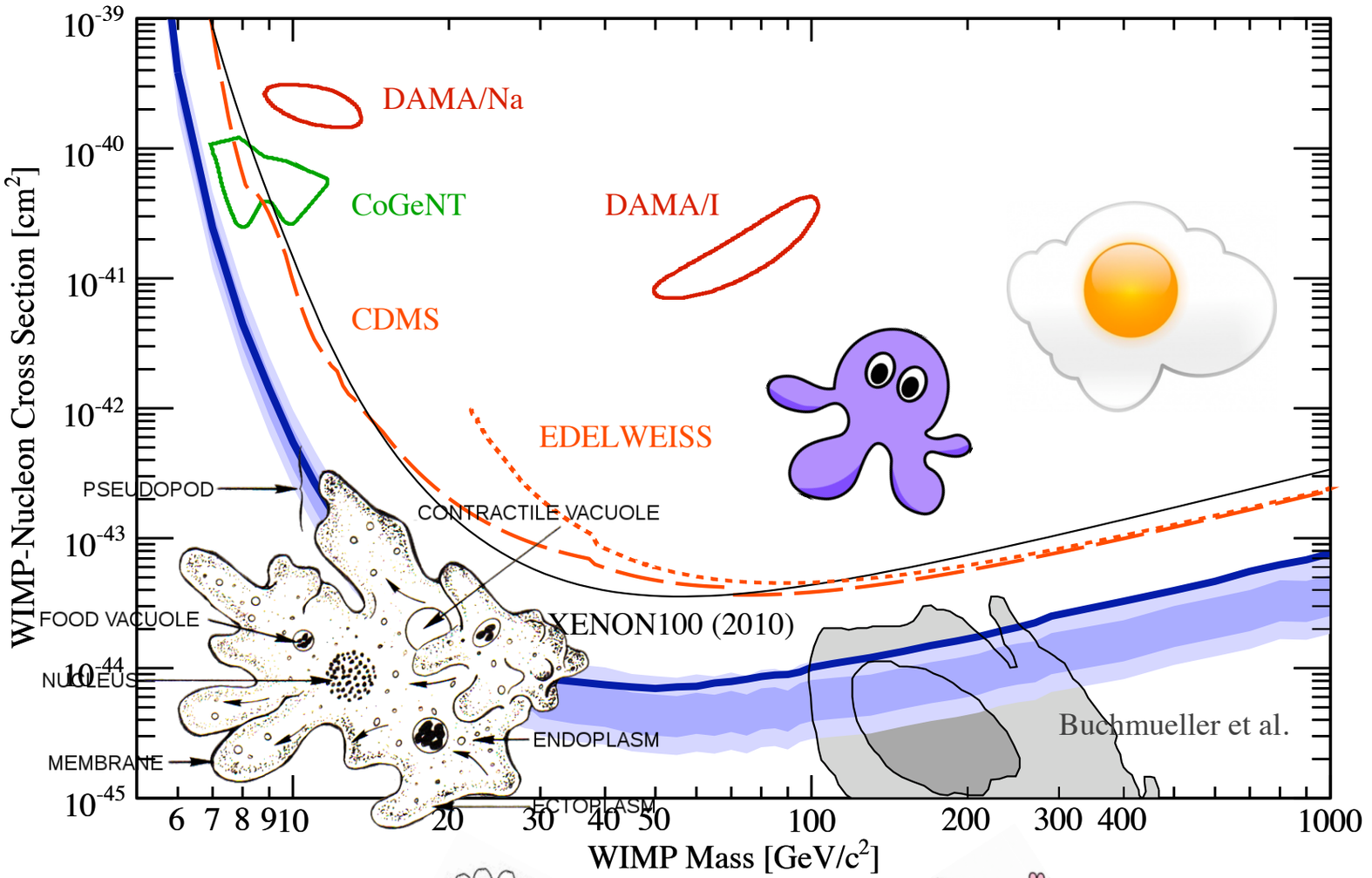
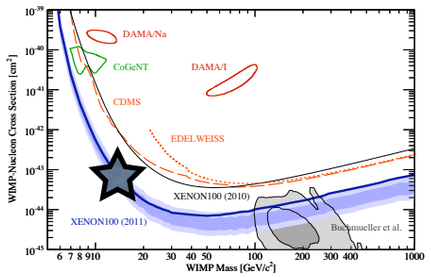
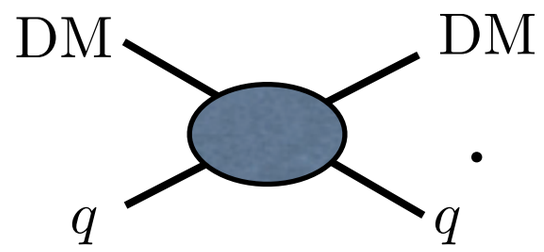


A Simple Point

* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

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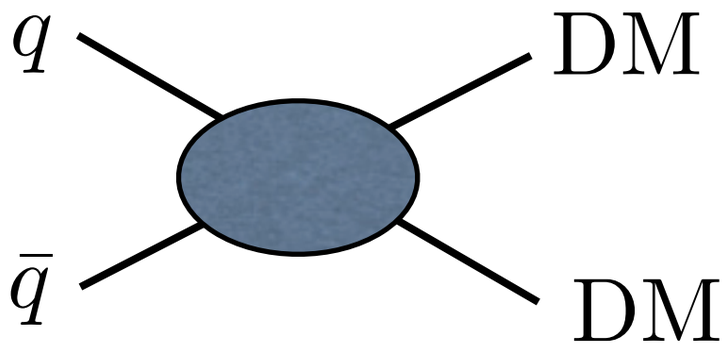
* The same interaction can lead to DM production at a hadron machine.



$$p\bar{p} \rightarrow \text{ nothing}$$

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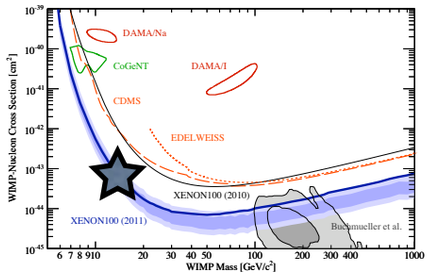
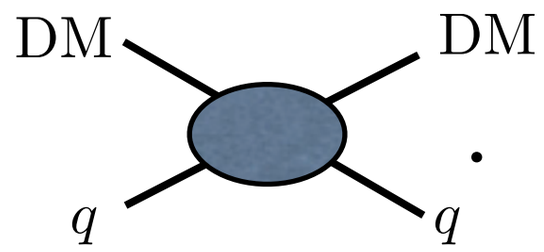
* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

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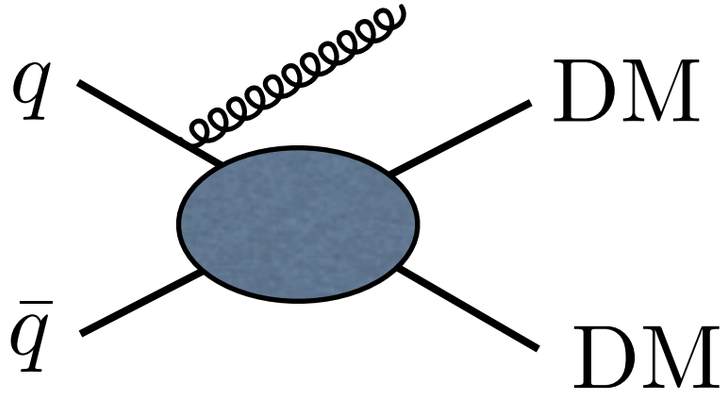
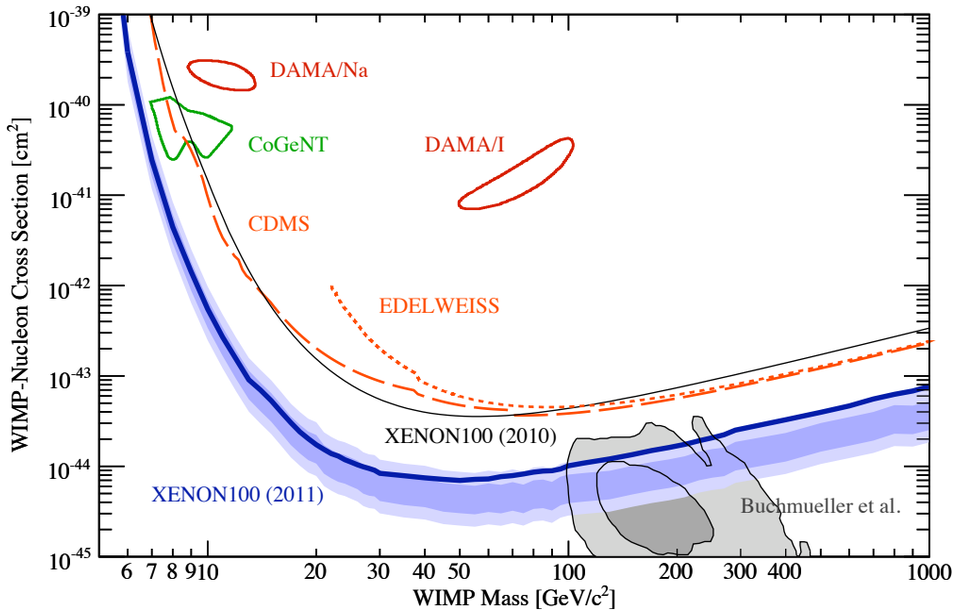
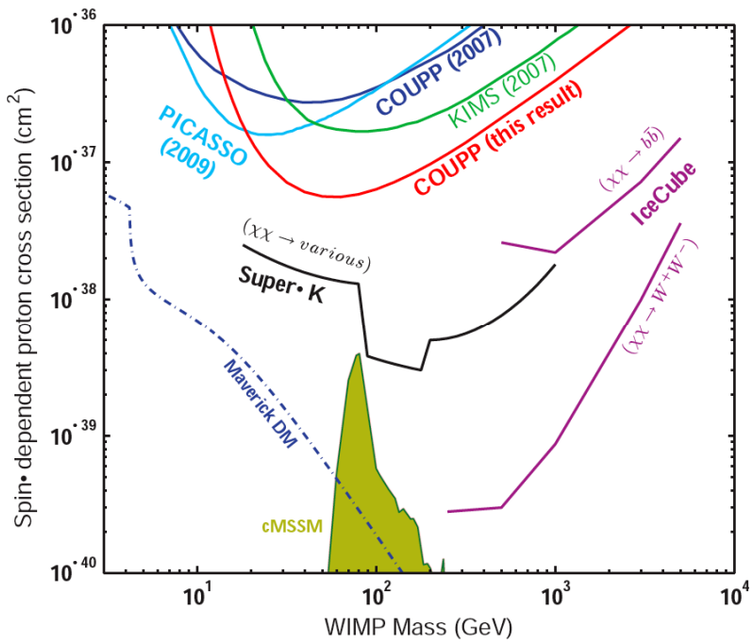


$$p\bar{p} \to j + \not{E}_T$$

A Simple Point

* **Mono-jet searches can place limits on the plane.**



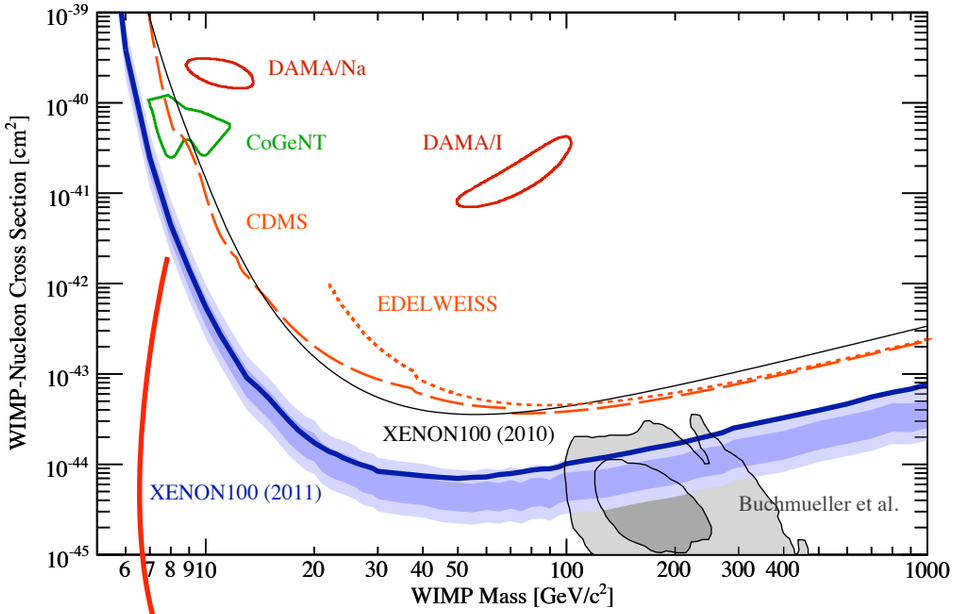


* These are **conservative** limits.
  In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

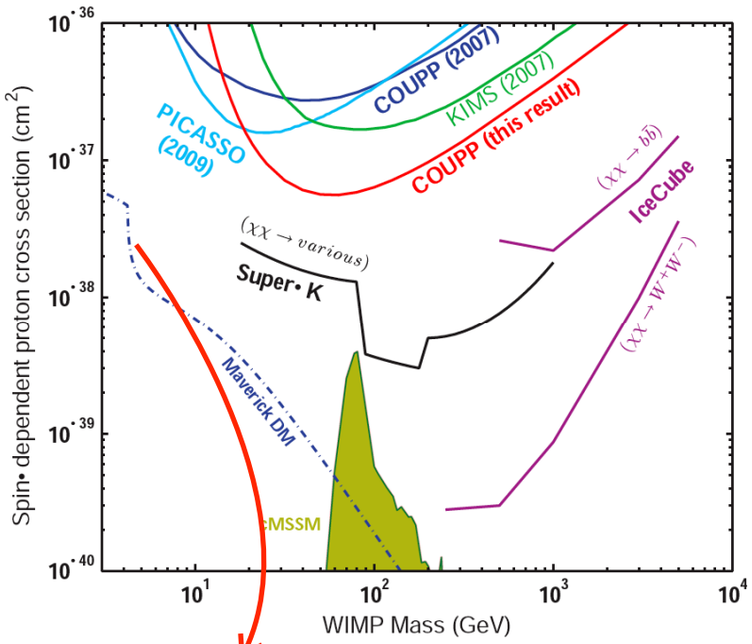
But mono-jet are certainly good to set bounds.

A Simple Point

- **Mono-jet searches can place limits on the plane.**



The collider does not have a low energy threshold



The collider does not pay a price for spin dependence

Setting Limits

Operators

* Describe DM interactions as higher DM operators (possibly mediated by light mediators)

$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q} q\right) \left(\bar{\chi} \chi\right) \,, \qquad \text{SI, scalar exchange}$$

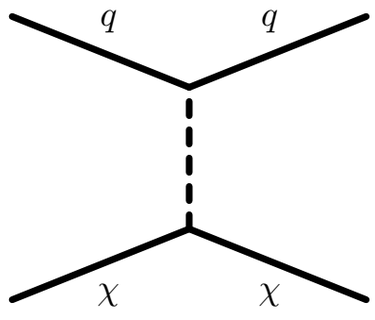
$$\mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q} \gamma_\mu q\right) \left(\bar{\chi} \gamma^\mu \chi\right) \,, \qquad \text{SI, vector exchange}$$

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q} \gamma_\mu \gamma_5 q\right) \left(\bar{\chi} \gamma^\mu \gamma_5 \chi\right) \,, \qquad \text{SD, axial-vector exchange}$$

$$\mathcal{O}_4 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q} \gamma_5 q\right) \left(\bar{\chi} \gamma_5 \chi\right) \,, \qquad \text{SD and mom. dep., psuedo-scalar exchange}$$

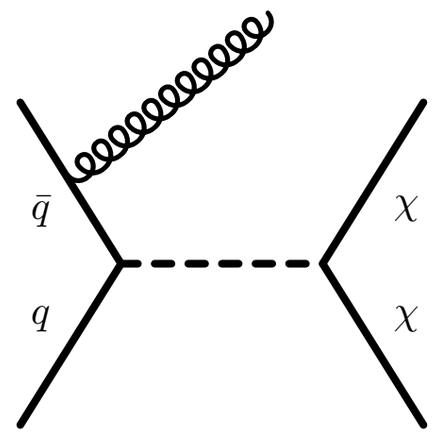
Cross Sections

* The direct detection cross section ($q \sim 100\ \mathrm{MeV}$):



$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4} \qquad \mu = \frac{m_\chi m_N}{m_N + m_\chi}$$

* Mono-jet + $\not{E}_T$ ($q \sim 10 - 100\ \mathrm{GeV}$):



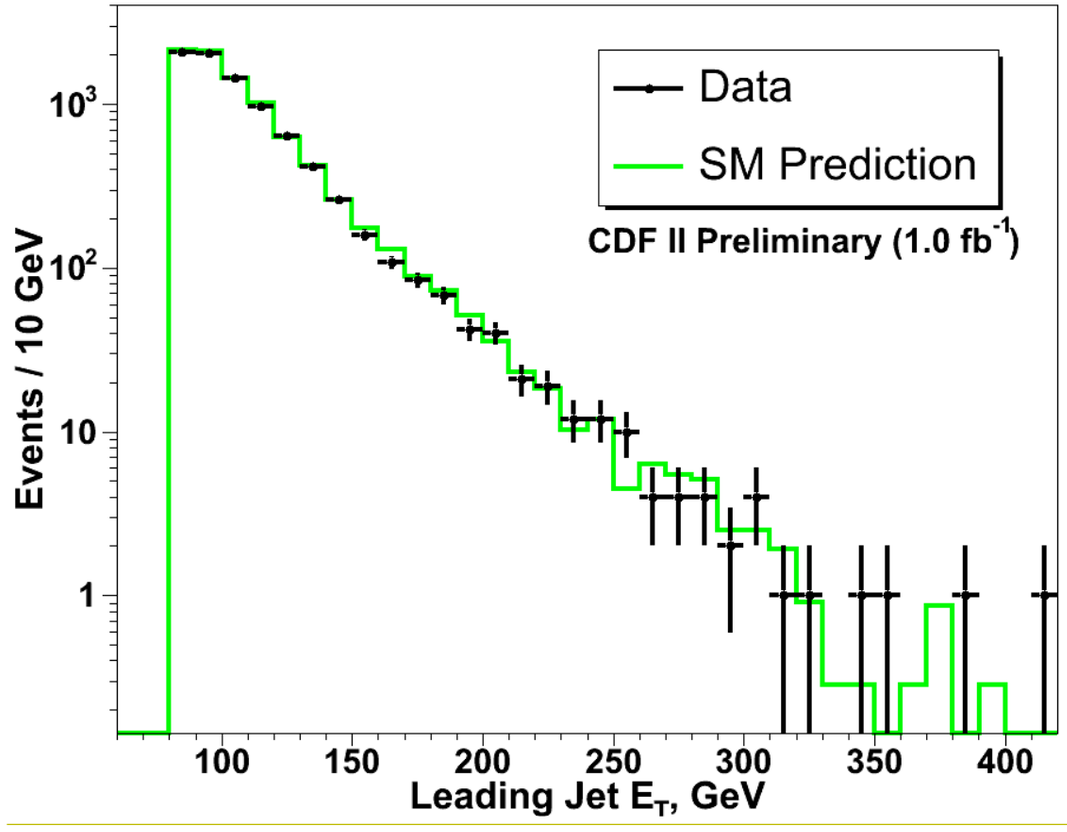
$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \lesssim 100\ \mathrm{GeV} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M \gtrsim 100\ \mathrm{GeV} \end{cases}$$

CDF: jet + MET (1fb^{-1})

counting experiment:

Observed: 8449 events
Expected: 8663+-332

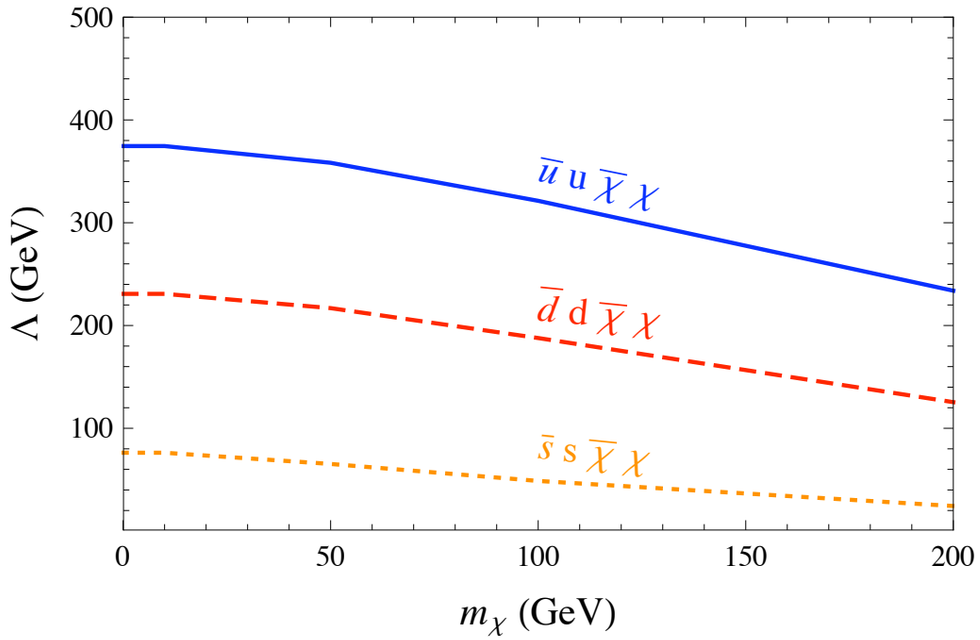
$$\not\!\!E_T > 80\,\mathrm{GeV}$$
$$p_T(j1) > 80\,\mathrm{GeV}$$
$$p_T(j2) < 30\,\mathrm{GeV}$$
$$p_T(j3) < 20\,\mathrm{GeV}$$

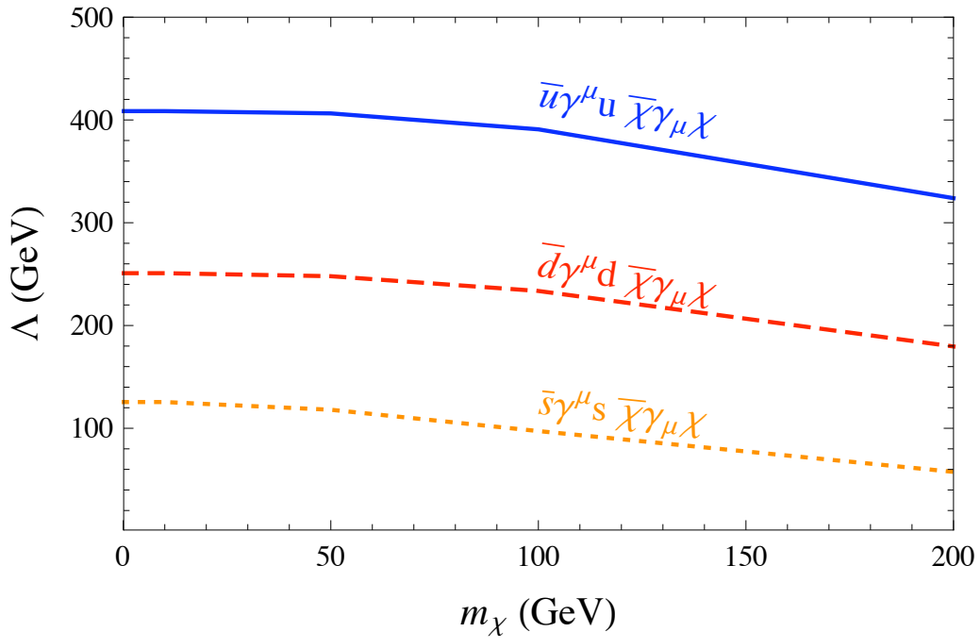


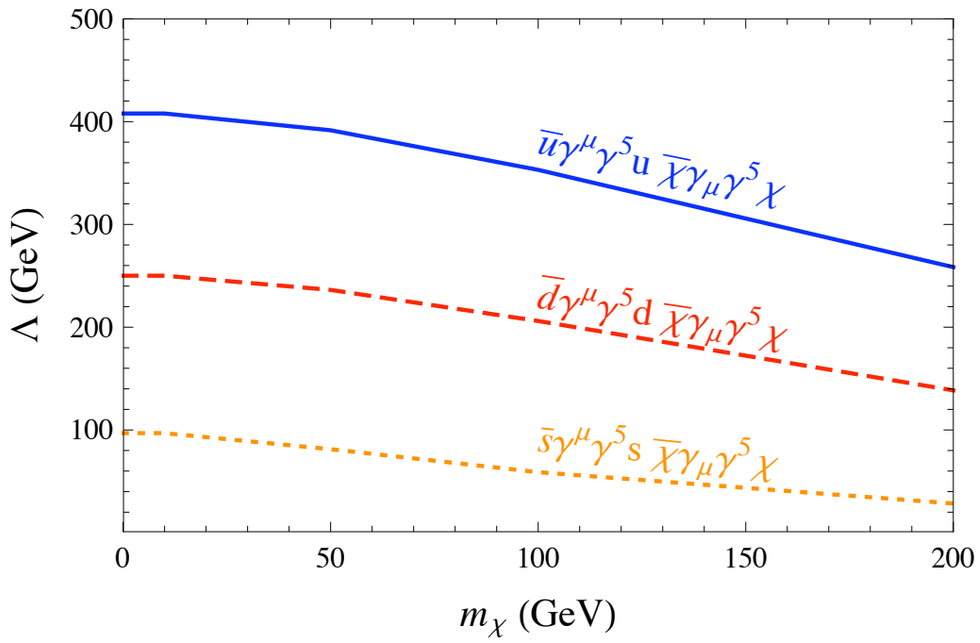
[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html]

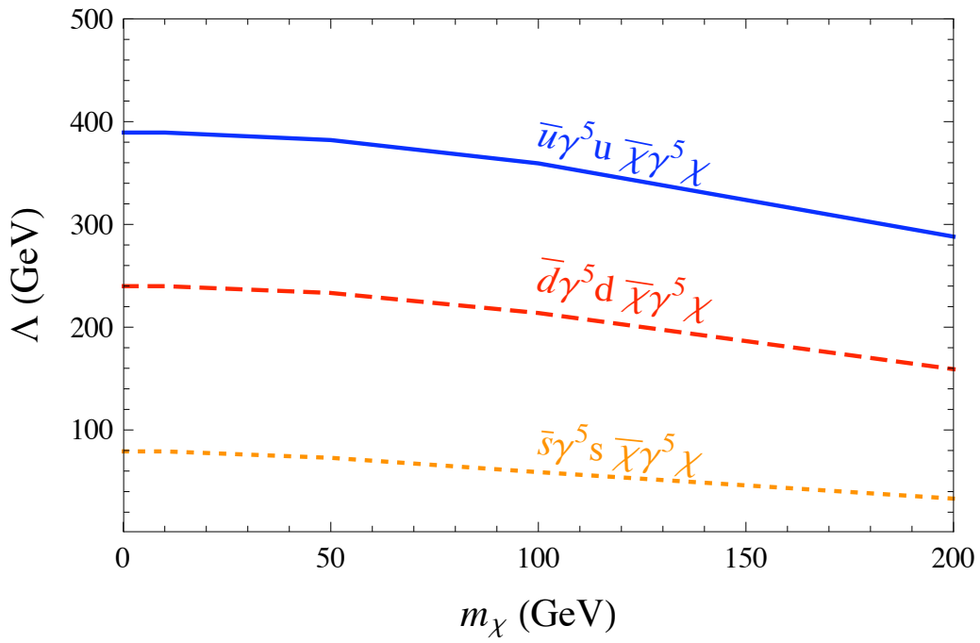
Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

* Operators are simple to implement.
  Limits on cutoff:









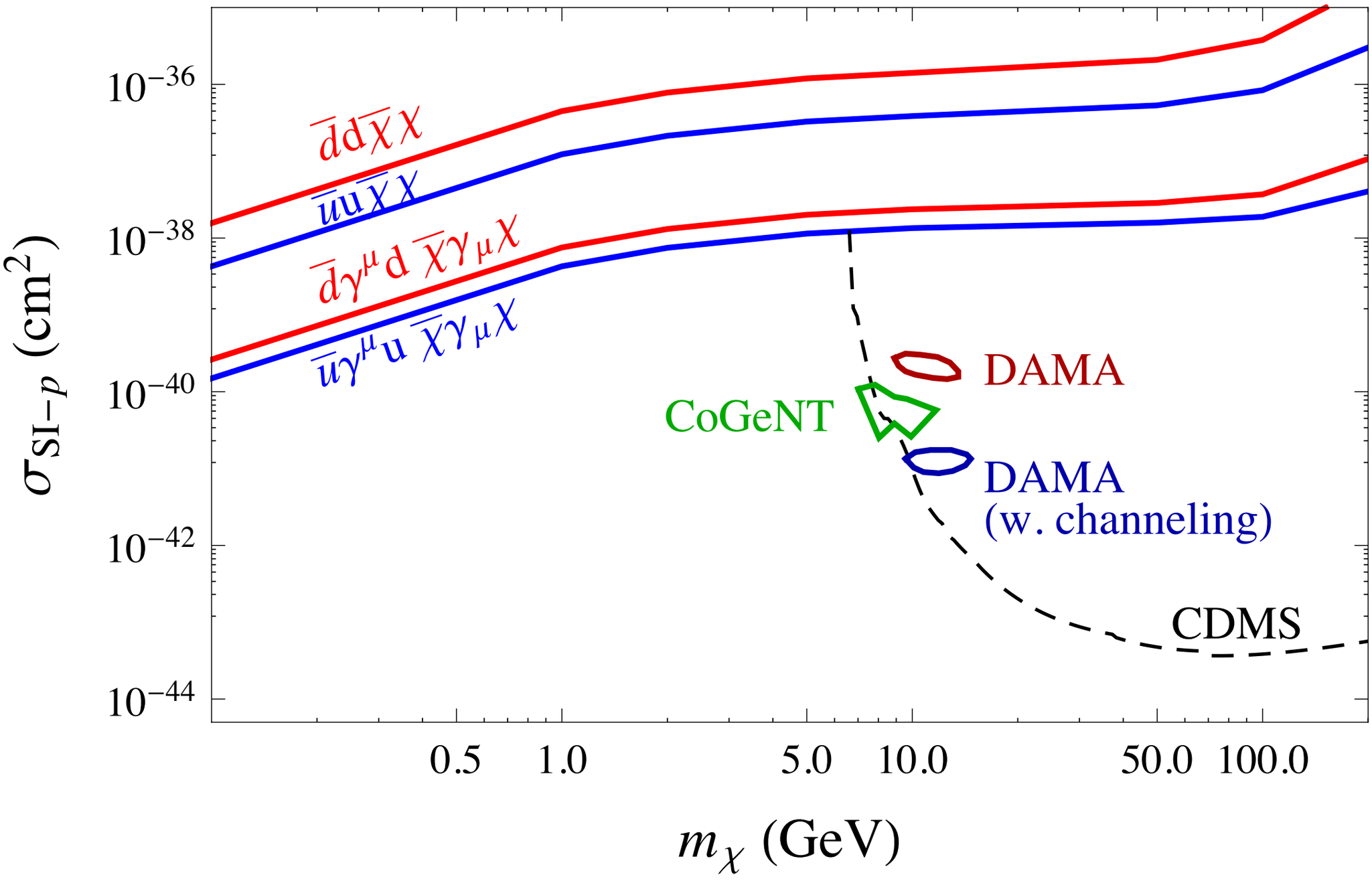
Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

* The limits are fairly flat in mass (up to ~200 GeV).
* The limits are fairly independent of the operator structure. Strong SD constraints.
* These limits apply to iDM - Tevatron doesn't care about 100 keV splittings.

SI Limit

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 ,$$

$$\sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2 ,$$



Best limit at low mass

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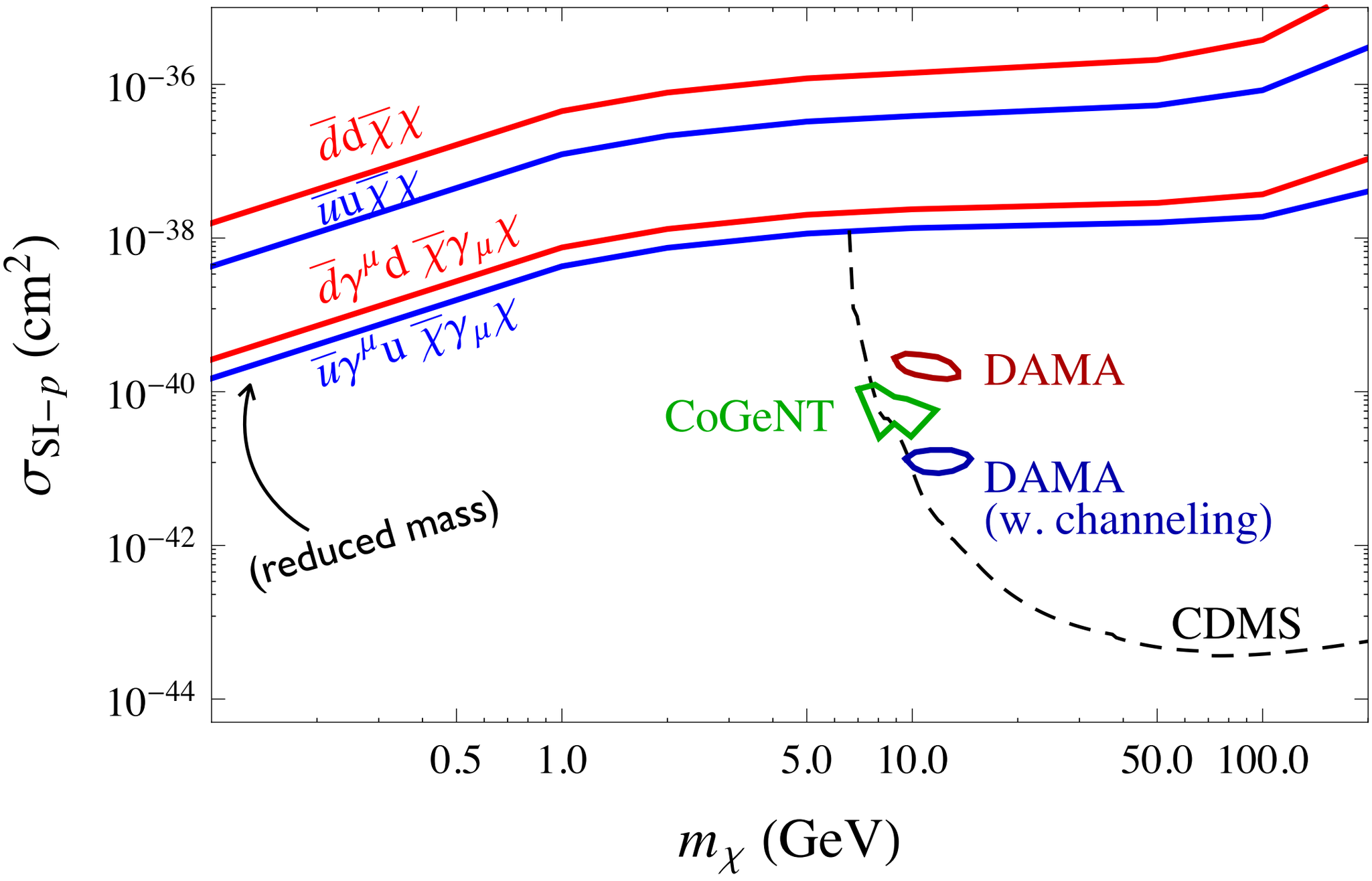
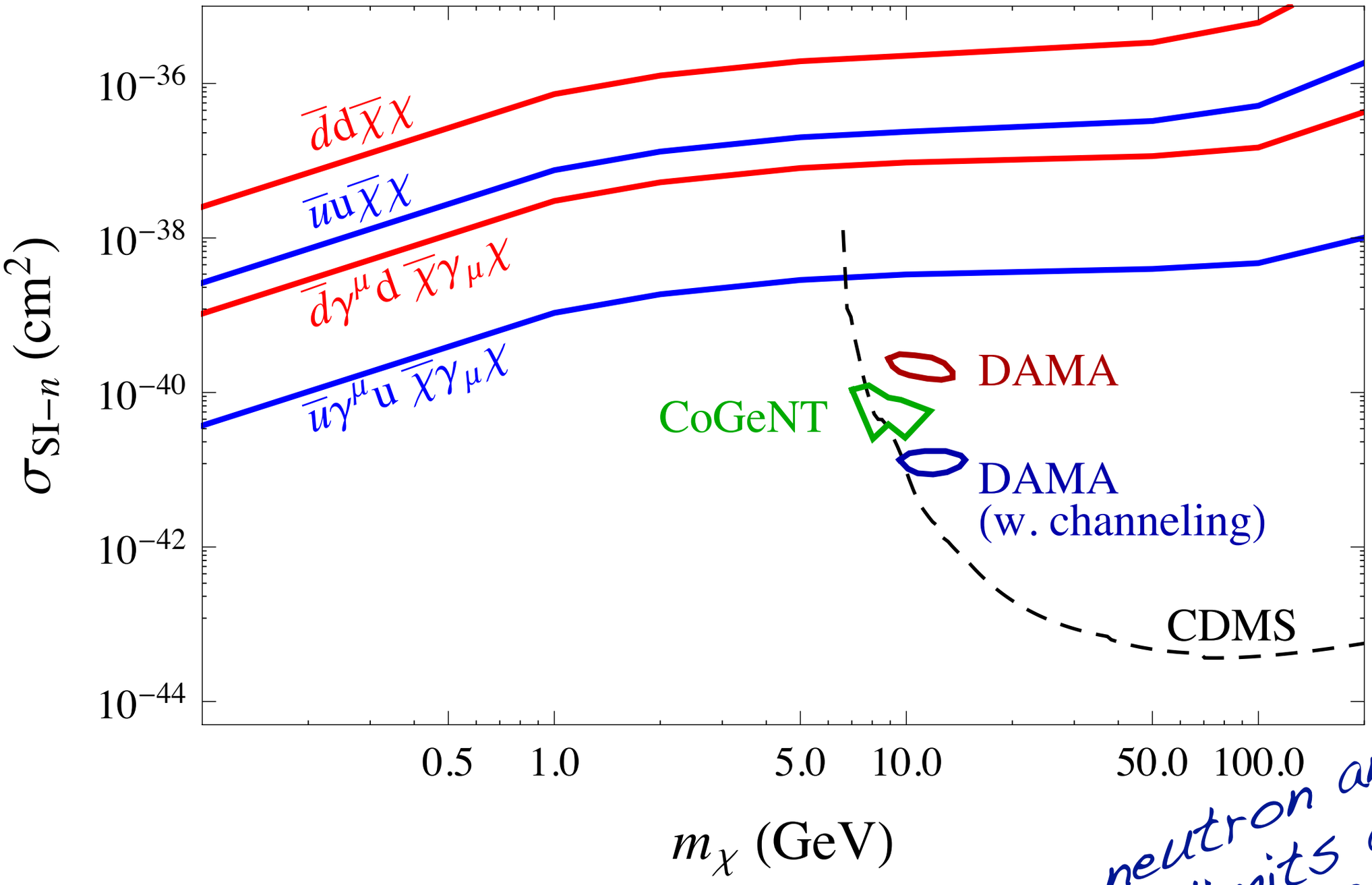


Best limit at low mass

SI Limit



neutron and proton limits are a bit different:

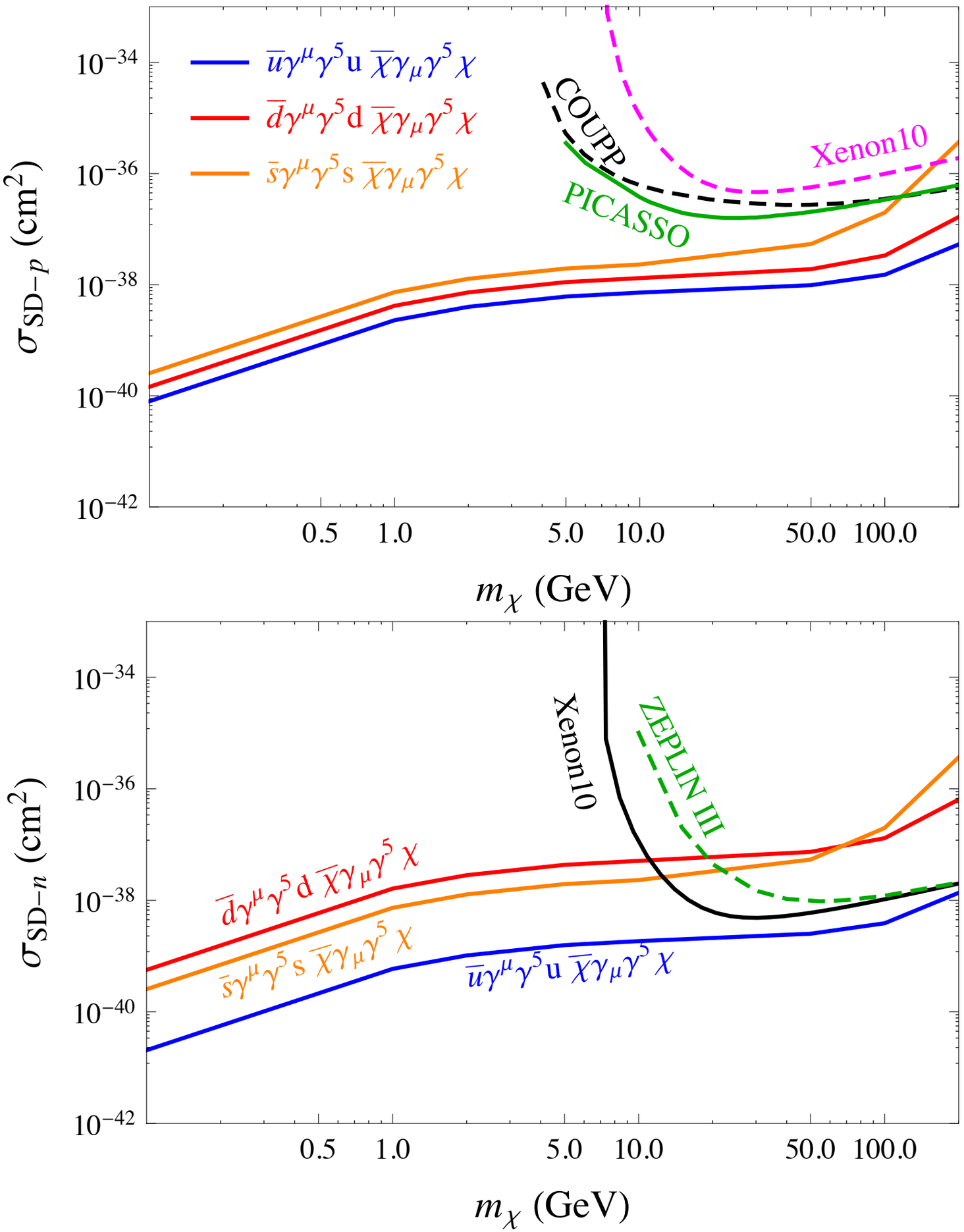
Best limit at low mass

SD Limits:

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

Best SD Limits over a wide mass range.

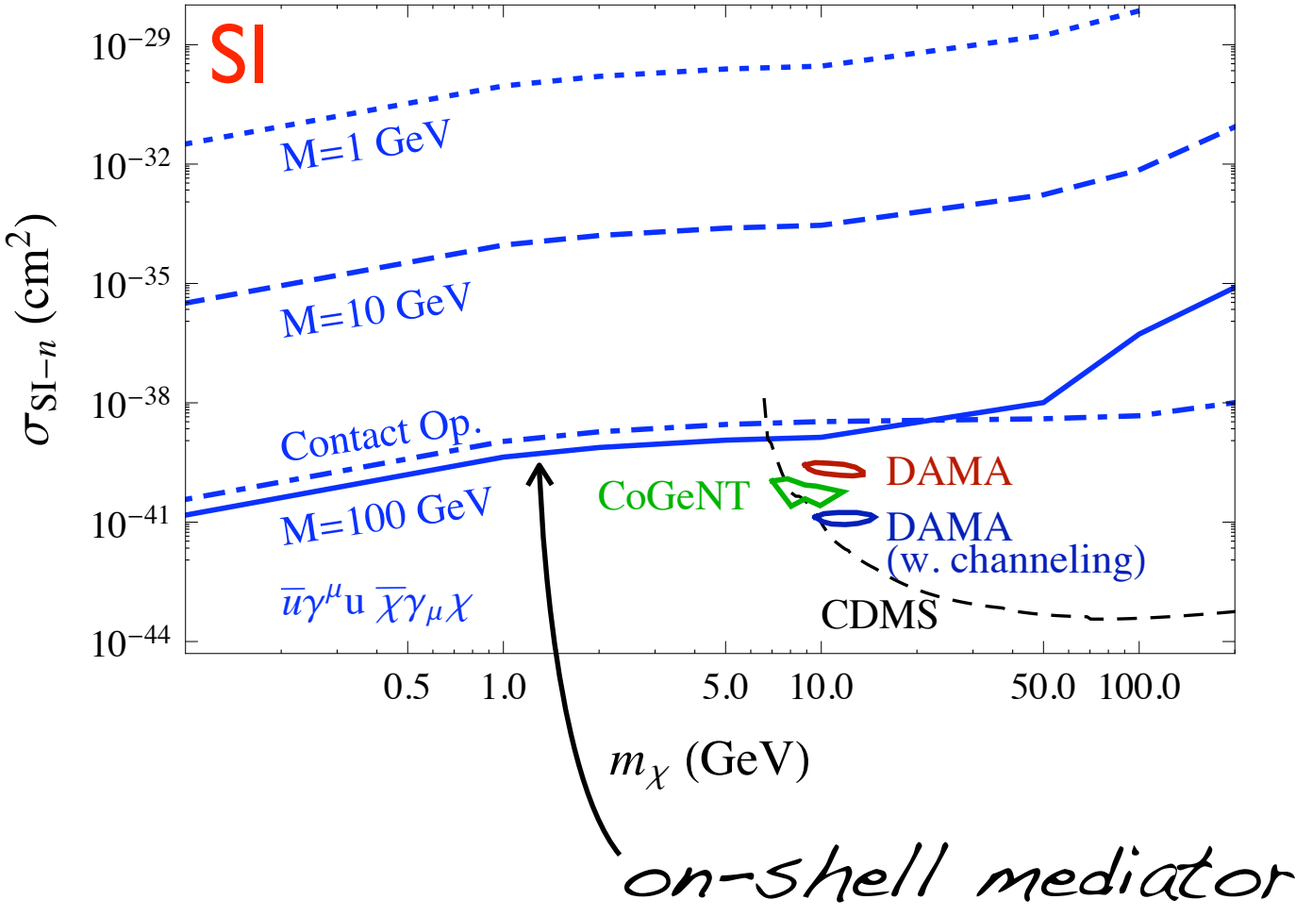
A dedicated CDF analysis underway!
(ATLAS and CMS too...)



Light Mediators

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \dfrac{\mu^2}{M^4}$ and lower M.

* Then $\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \dfrac{1}{p_T^2}$ drops as M^4.



Collider limit is lost for light mediators.

Direct detection discovery in conflict with LHC searches = discovery of light mediator...!?

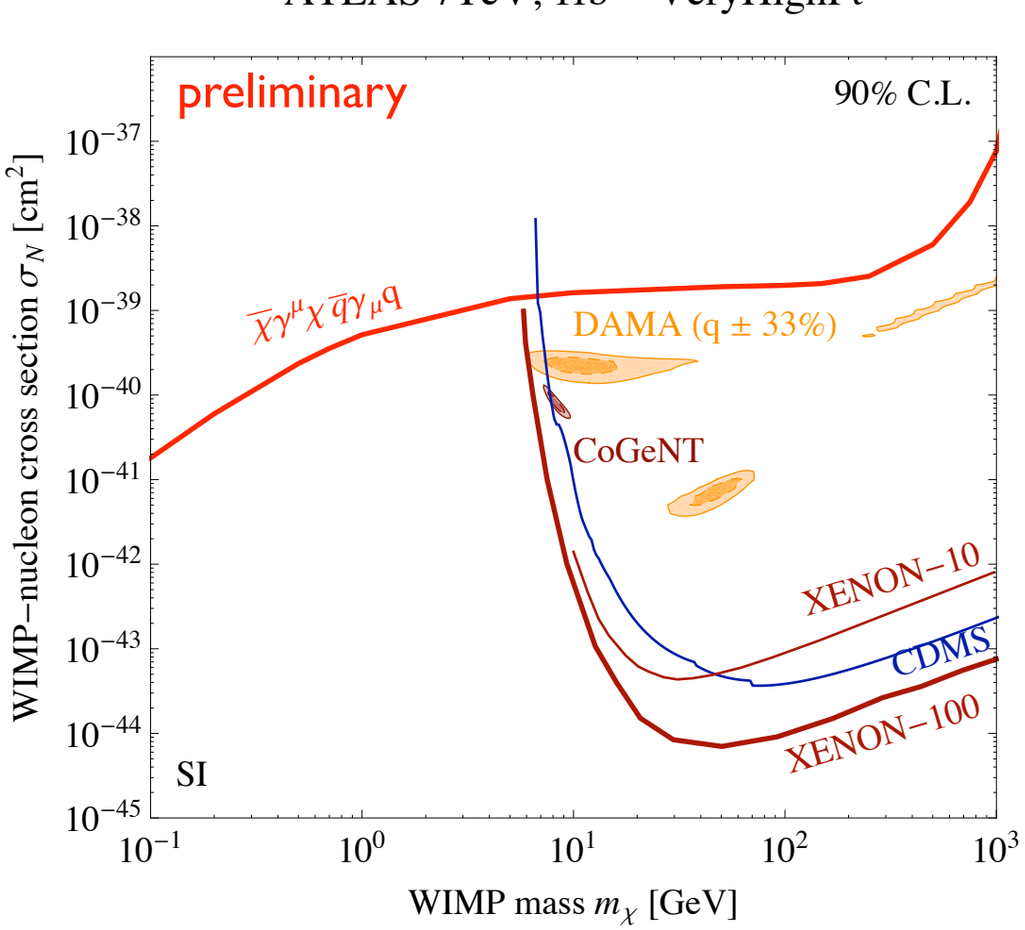
Future Prospects:

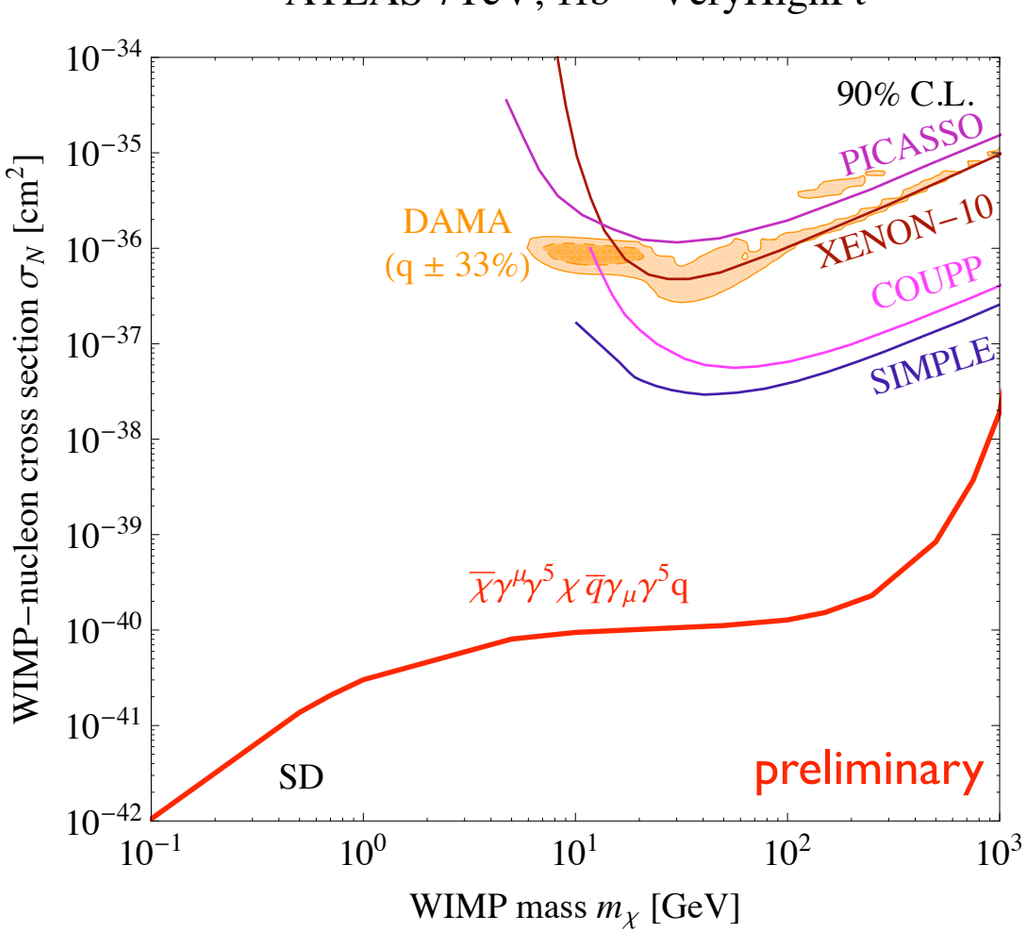
The Future started a month ago!

LHC!

LHC Mono-jets

* Both CMS and ATLAS have several mono-jet searches:





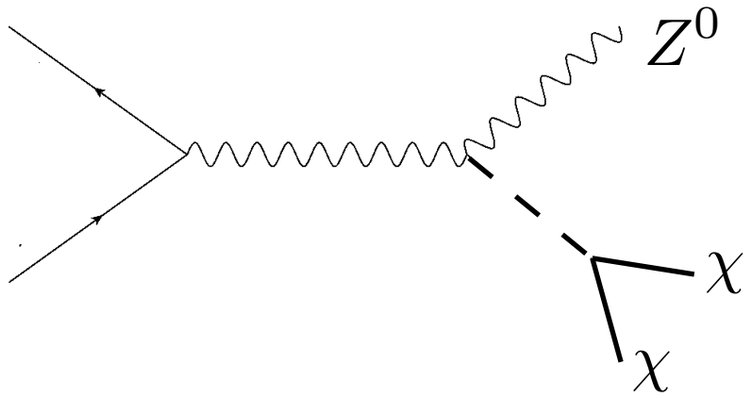
Yu-hsin's talk:

the various LHC mono-jet analyses and how they may be improved!

(in ~30 minutes, after "Dark Matter Beams", also recommended!)

Mono-something!

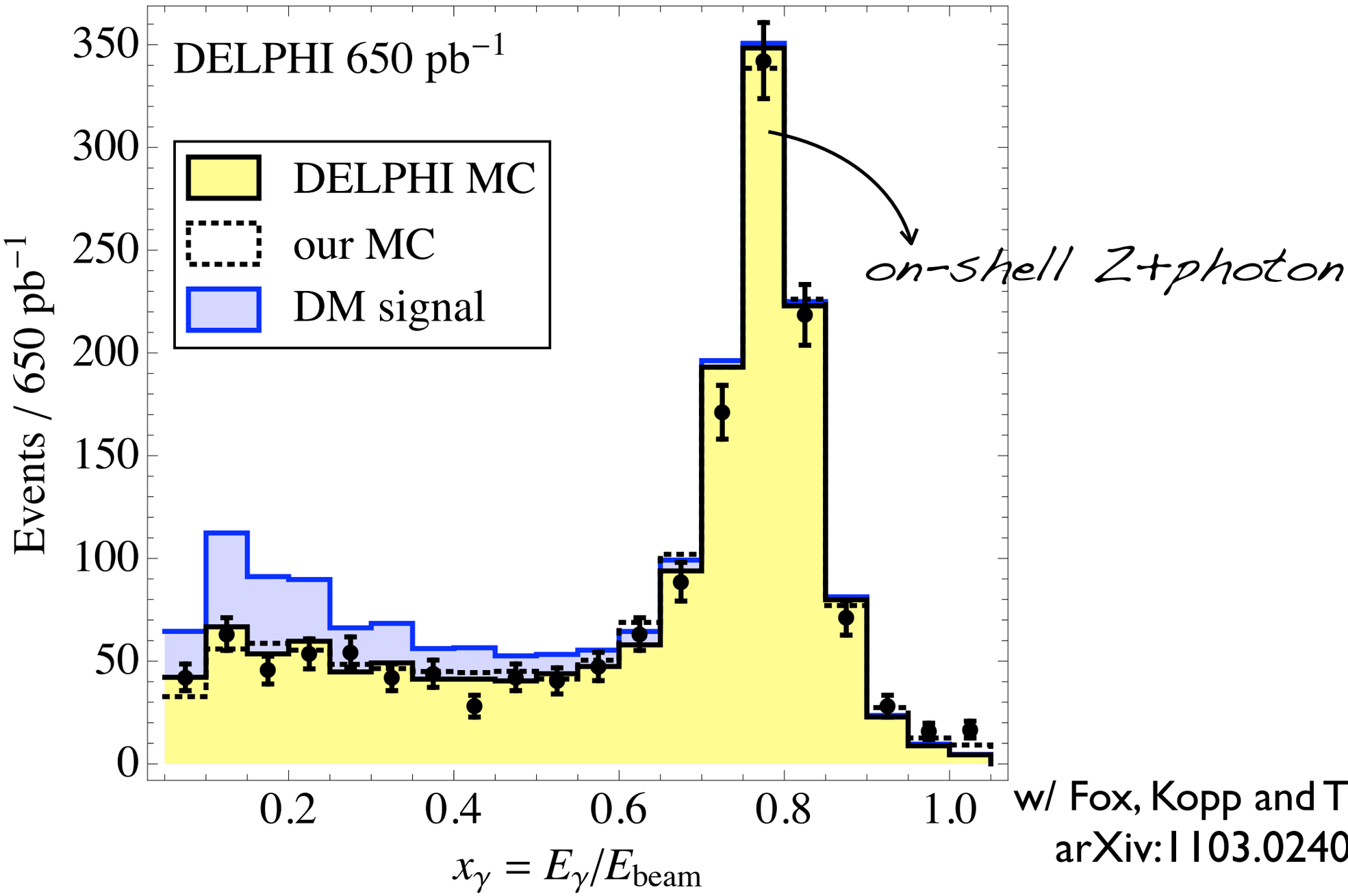
* We can probe DM-SM interactions further with other "mono-somethings".
* **Mono-photon** at LHC. First CMS study out.
* **Mono-photon** at LEP! For DM-lepton interactions.
* **Mono-top** in MFV (kamenik and Zupan).
* In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.



Invisible Higgs searches can be interpreted as "direct detection" experiments!

LEP Mono-photon

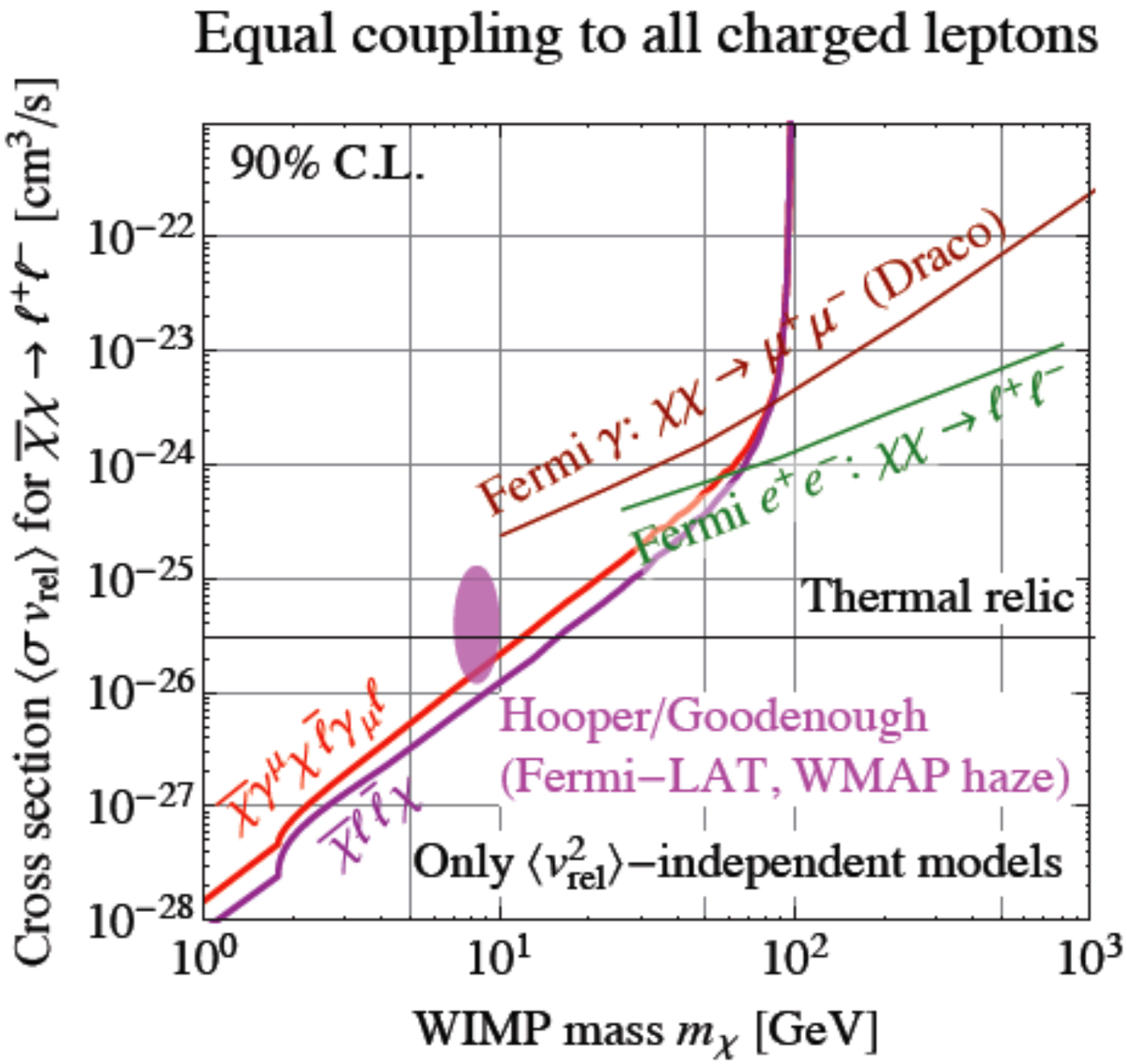
* Use spectrum shape to reject background peak.



w/ Fox, Kopp and Tsai
arXiv:1103.0240

LEP and Indirect Searches

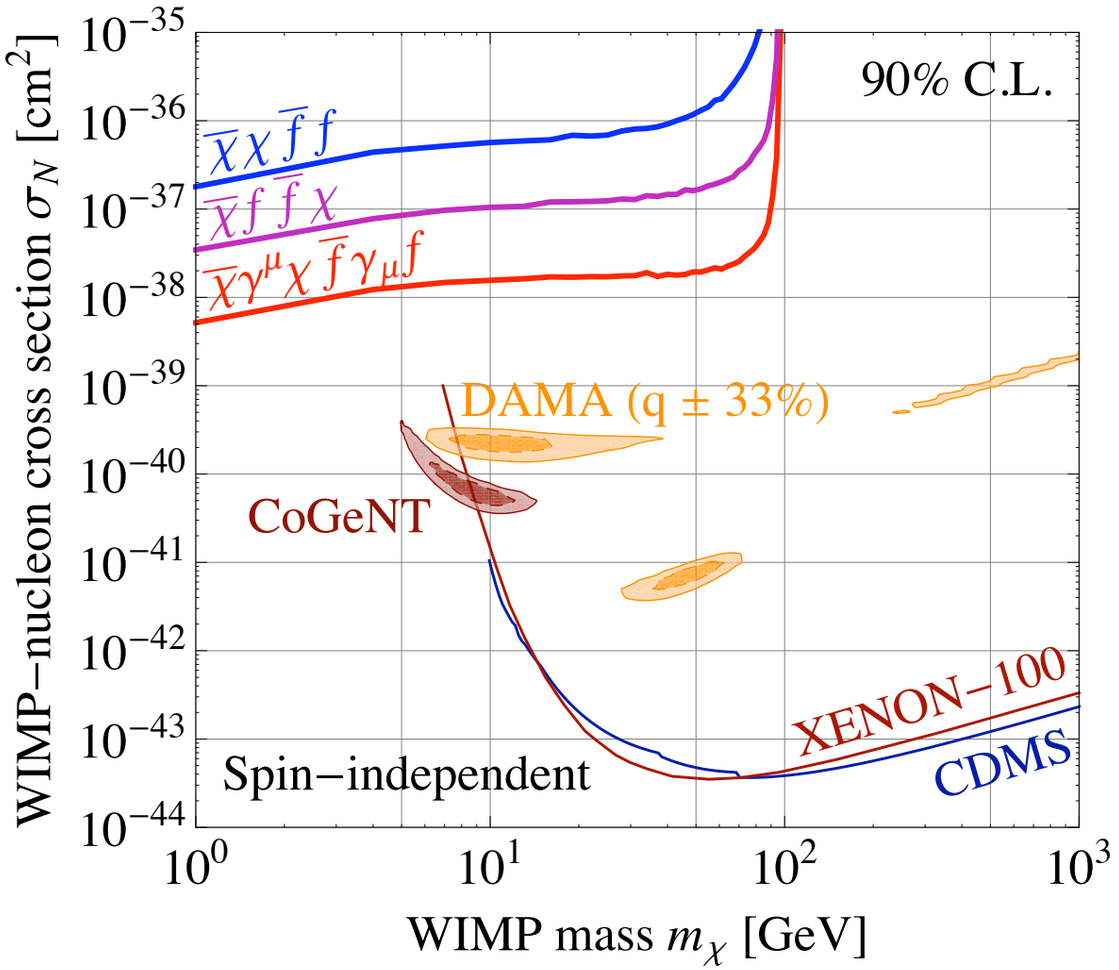
* DM couplings to leptons is also probed by Fermi:



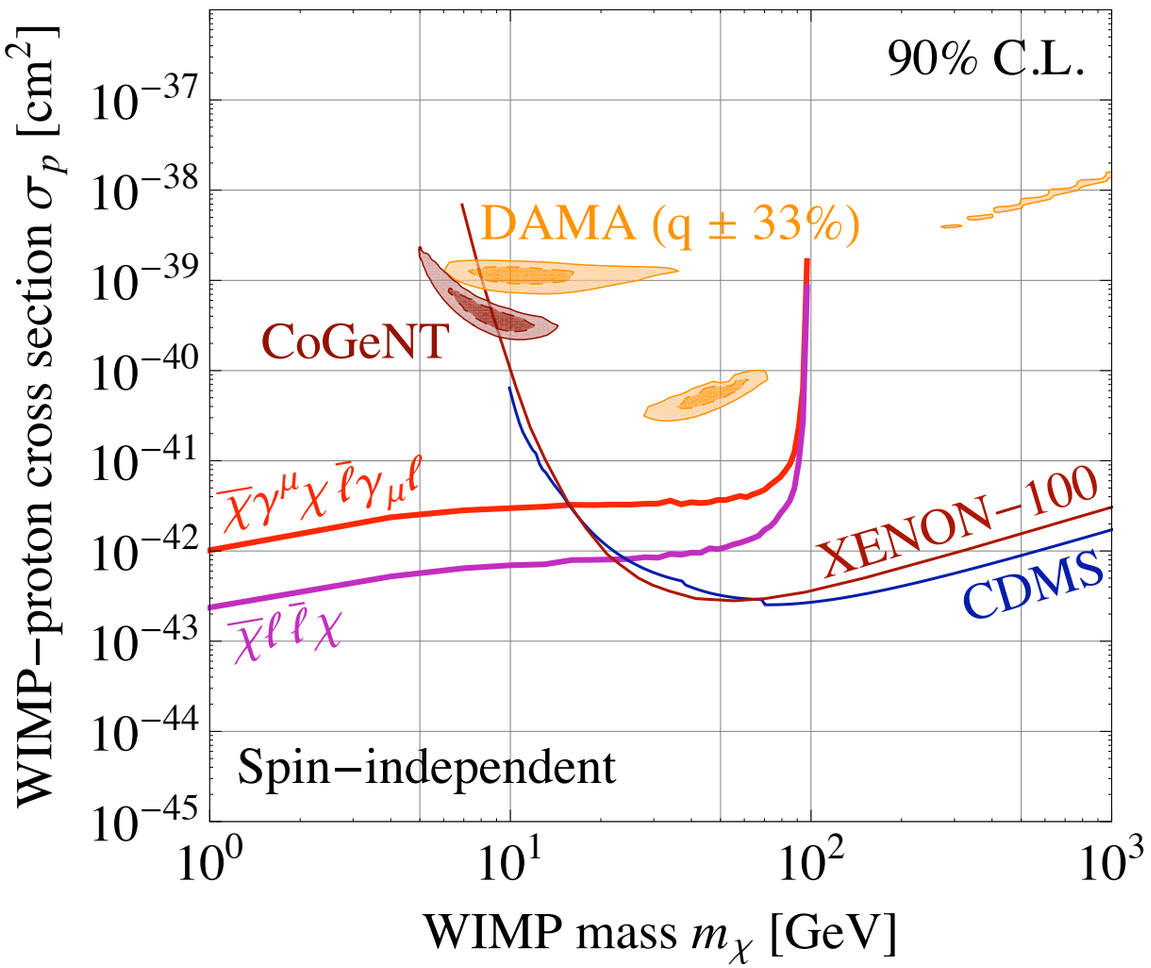
LEP wins at low mass & constrains the Hooperon.

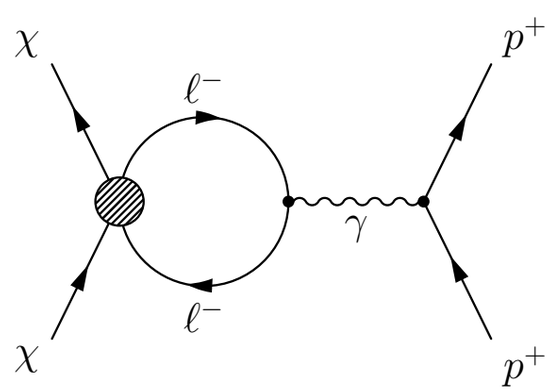
LEP DD Limits

Equal couplings to all SM fermions

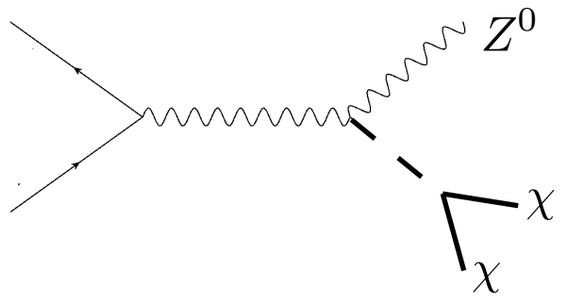


Couplings to leptons only

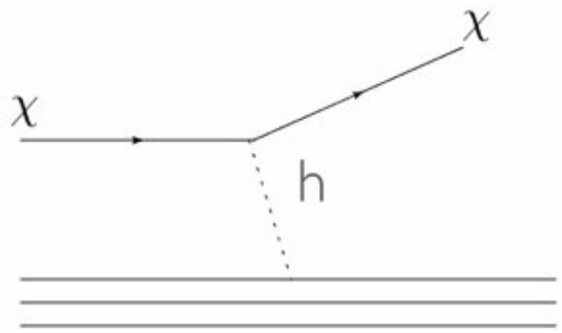




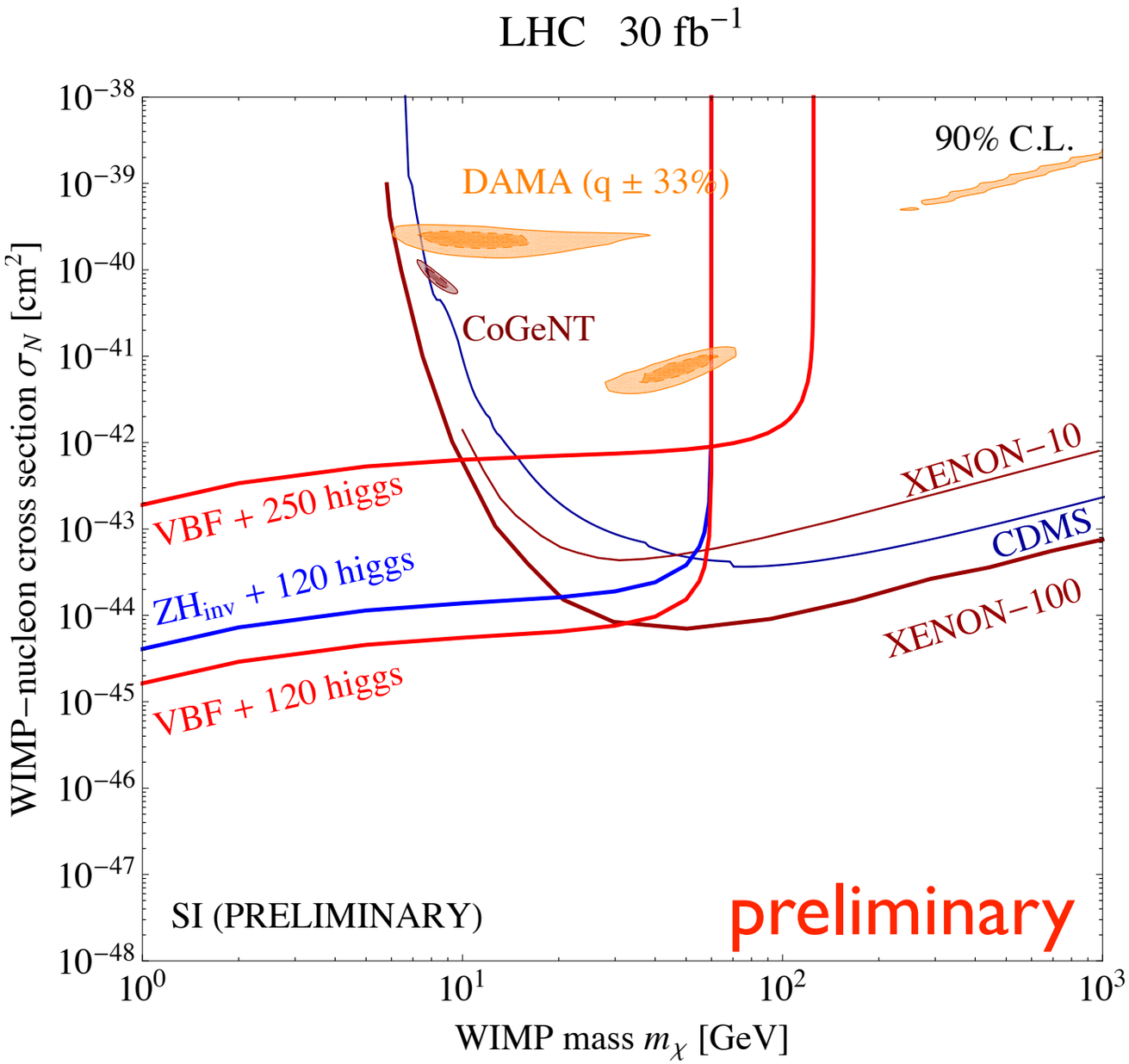
Higgs Mediator



vs.



Direct detection is parametrically smaller.



A characteristic Higgs-coupled-DM signal.

May uncover the identity of the mediator!

In progress, with Fox, Kopp and Tsai

To Conclude:

Colliders are placing competitive and complementary bounds to direct detection:

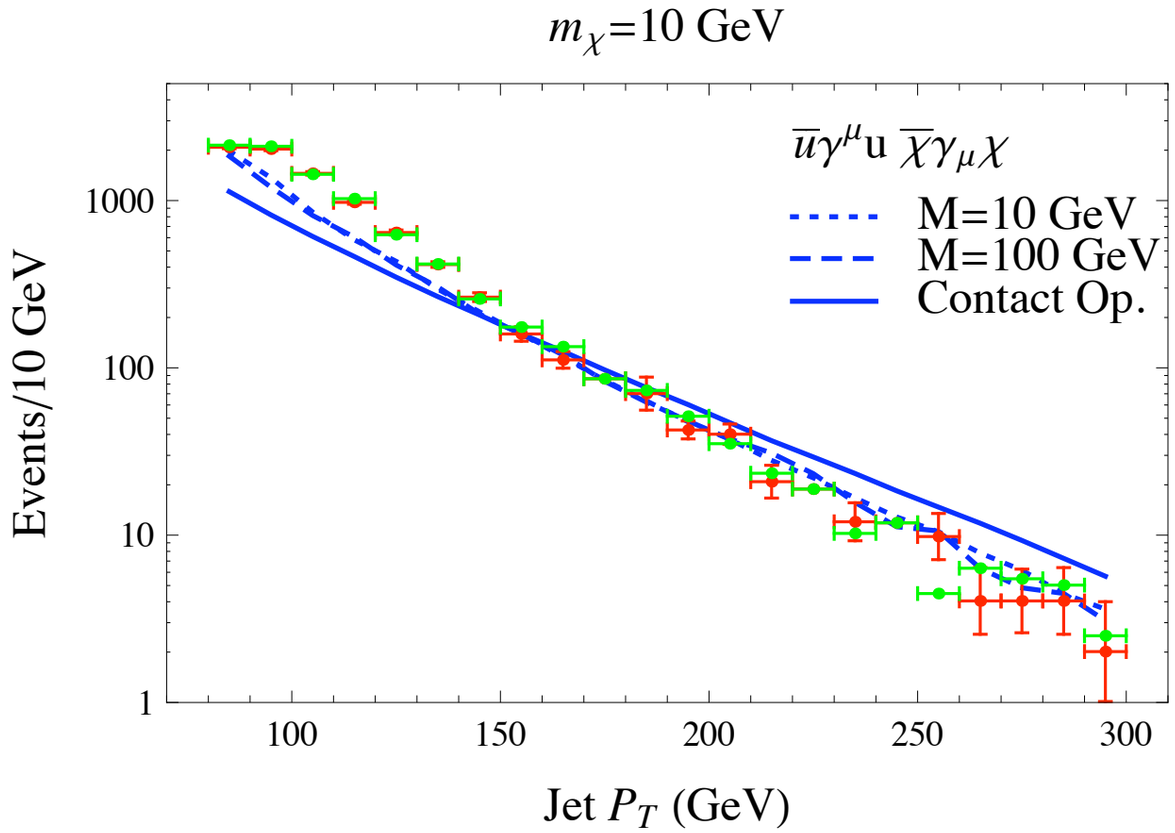
* The **Tevatron** (LHC) is the world record holder for light dark matter and for spin dependent.
* Dedicated CDF, CMS, ATLAS **mono-jet** studies are underway.
* **LEP** mono-photons provide strong constraints.
* The **LHC** can also be competitive in the case of **scattering through the Higgs**. May identify the the Higgs as the mediator.

Extra! Extra!

* Read all about it!

Future

* Shape:



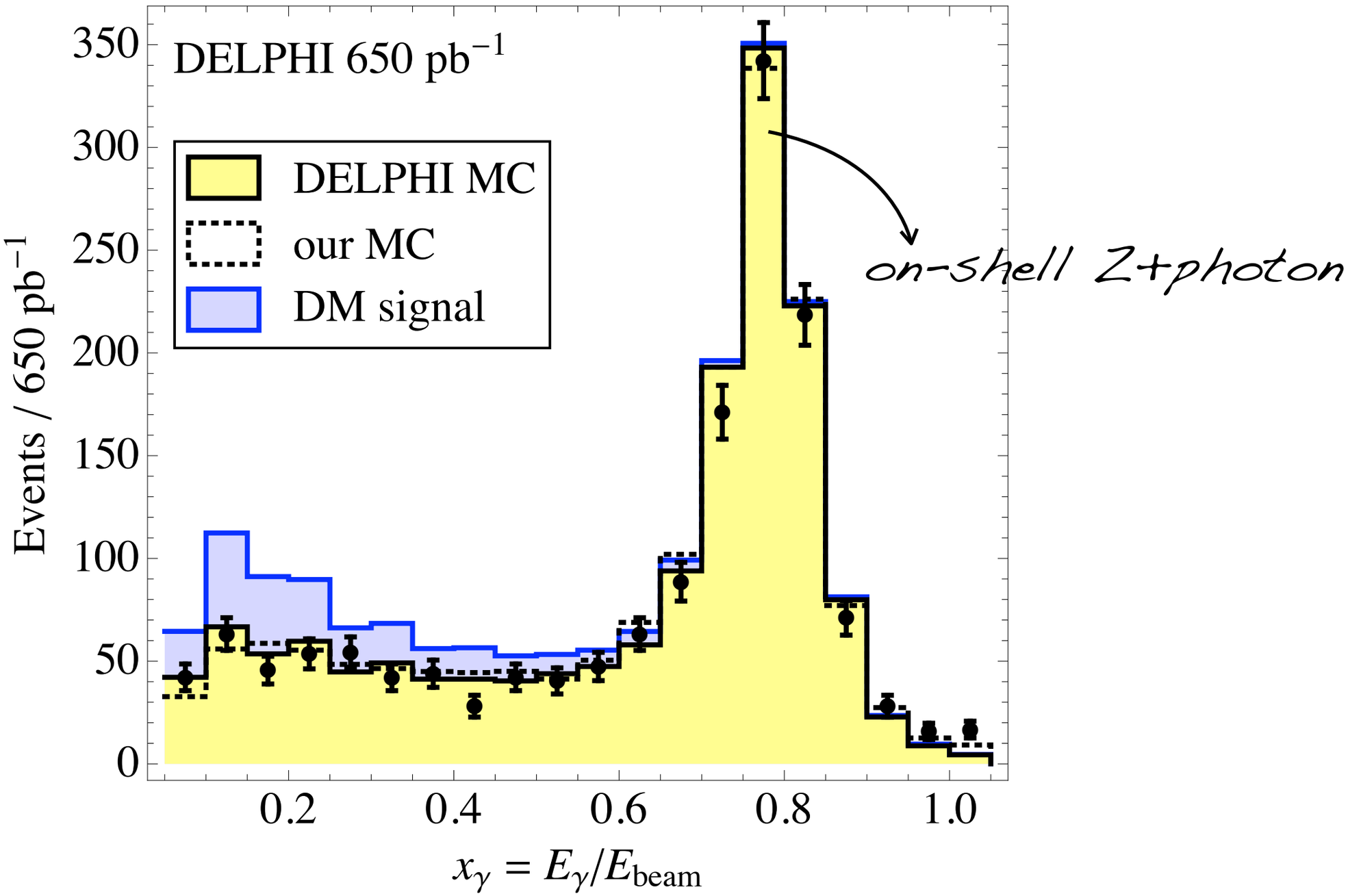
* A dedicated analysis may be more powerful.
* CDF is working on a dedicated analysis!
* So are CMS and ATLAS!
* Mono-photon is also be interesting, complementary.

LEP

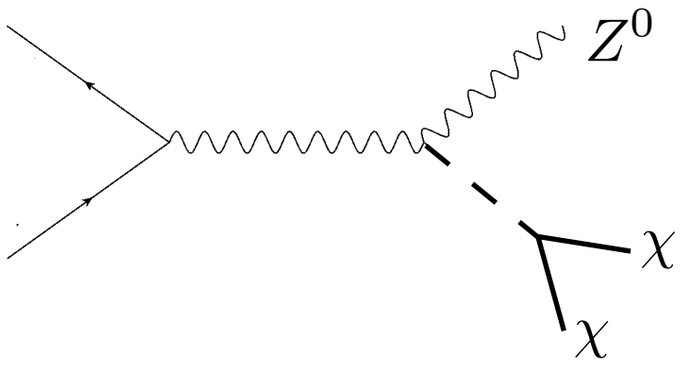
* Directly constrain DM coupling to electrons.
* **But**, in many models quark and lepton coupling are related (consider 2 benchmarks).
* LEP is a clean environment. Ability to measure missing mass.
* Places non-trivial limits also on indirect searches in lepton channels (e.g. the Hooperon).

Mono-photon

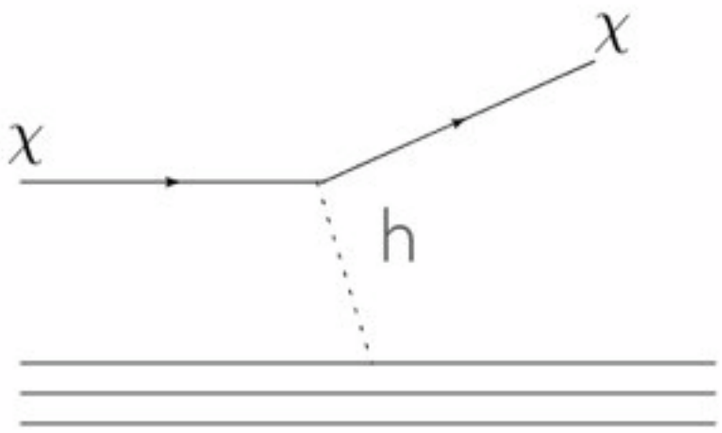
* Use spectrum shape to reject background peak.

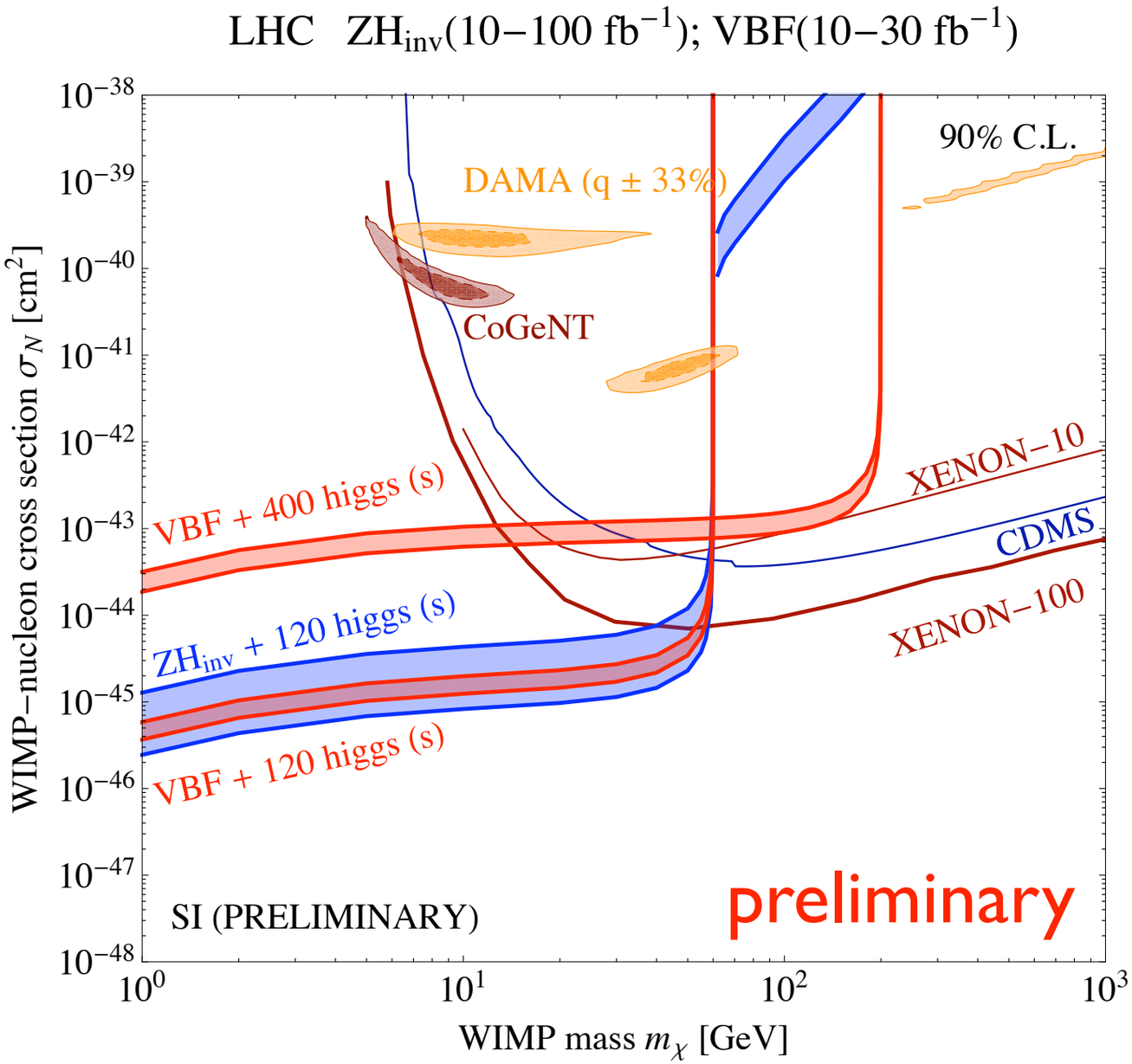


Higgs Mediator



vs.





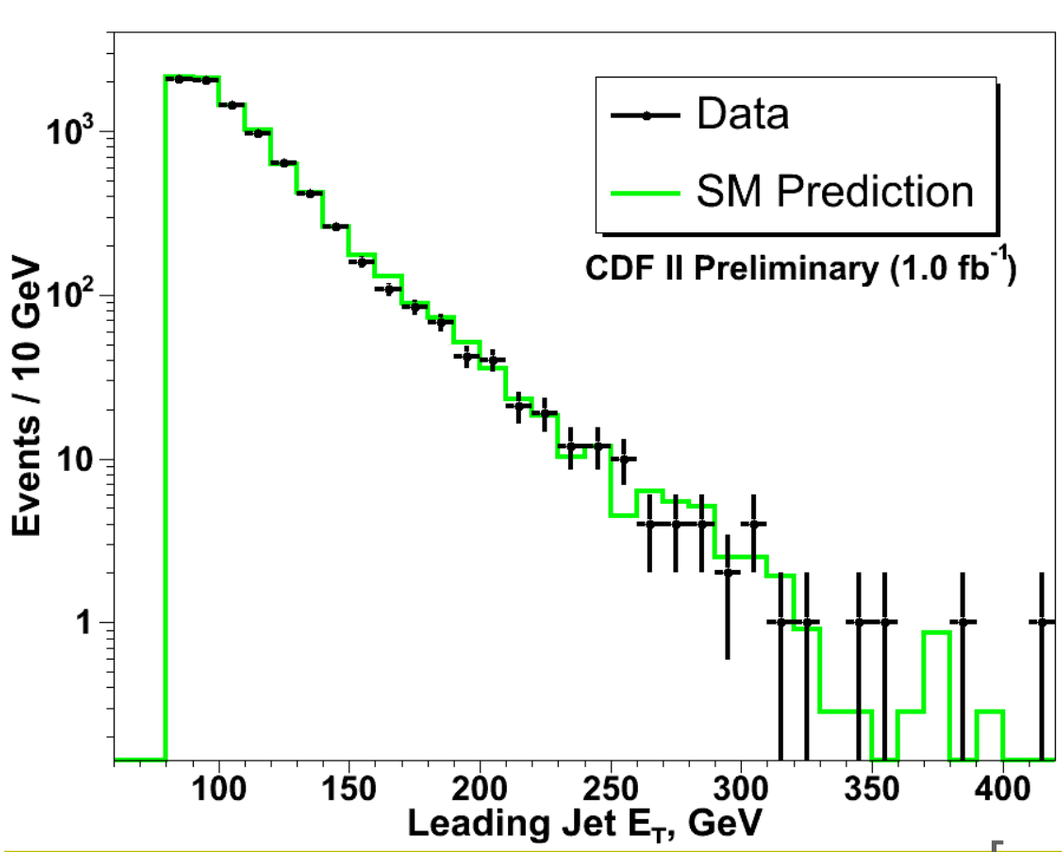
Direct detection is parametrically smaller!

In progress, with Fox Kopp and Tsai

CDF: jet + MET (1 fb^{-1})

counting experiment:

$$\not\!\!E_T > 80\,\mathrm{GeV}$$
$$p_T(j1) > 80\,\mathrm{GeV}$$
$$p_T(j2) < 30\,\mathrm{GeV}$$
$$p_T(j3) < 20\,\mathrm{GeV}$$



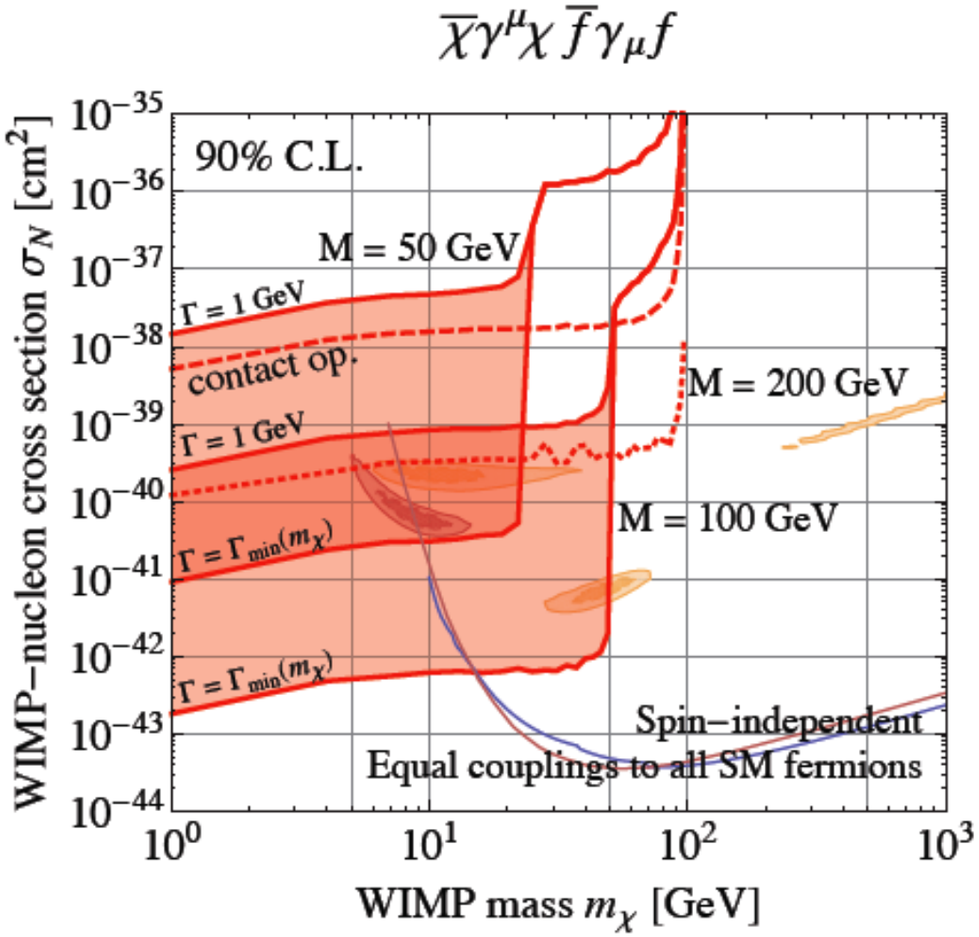
Background	Number of Events
Z -> nu nu	3203 +/- 137
W -> tau nu	2010 +/- 69
W -> mu nu	1570 +/- 54
W -> e nu	824 +/- 28
Z -> ll	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

Observed: 8449 events

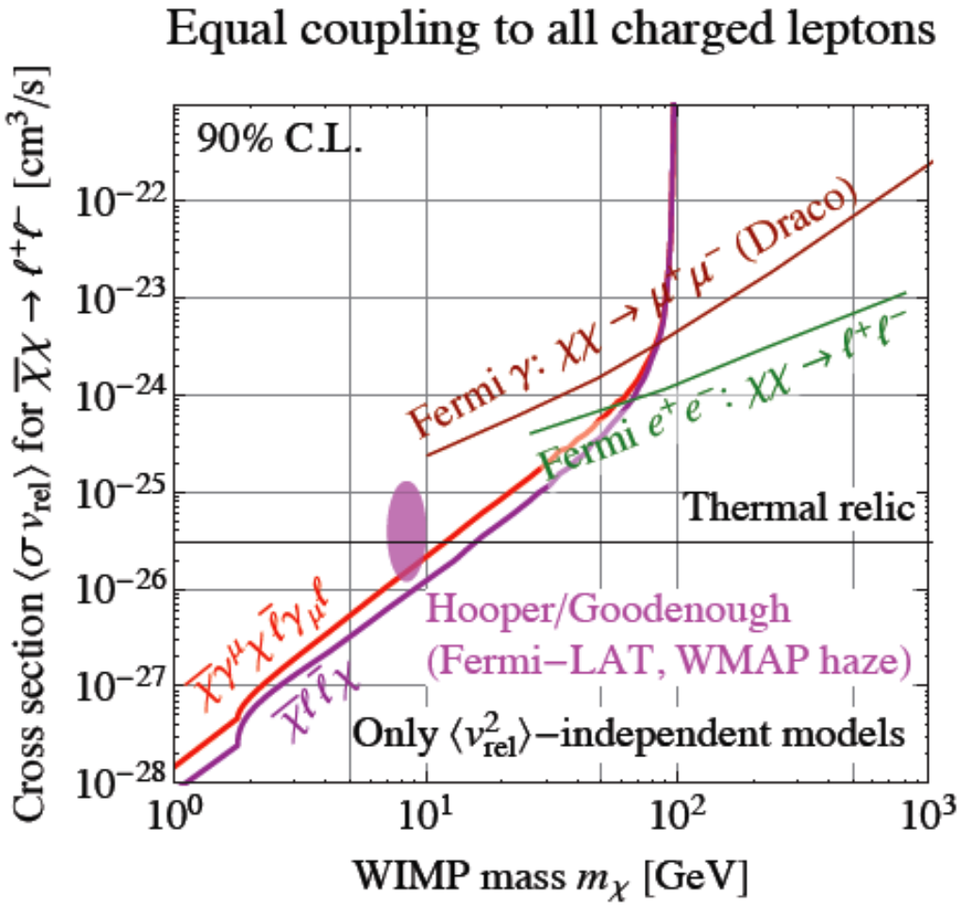
[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html]

Many more..

* Light mediators:

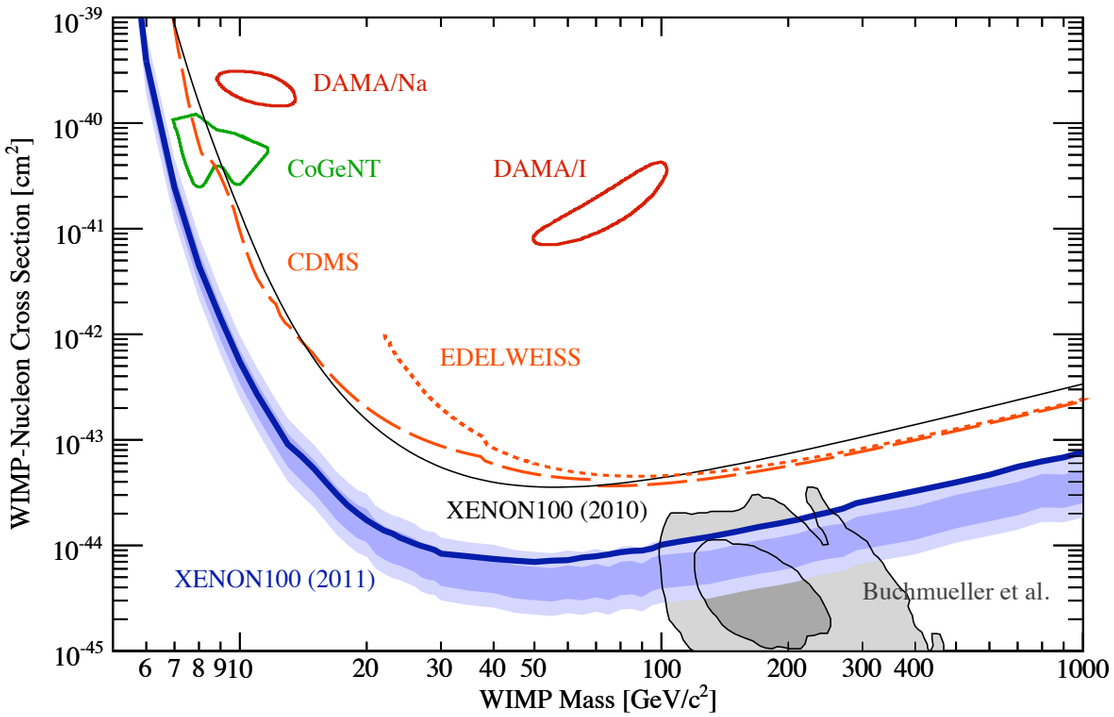


* Indirect detection:



Collider Connections?

* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).



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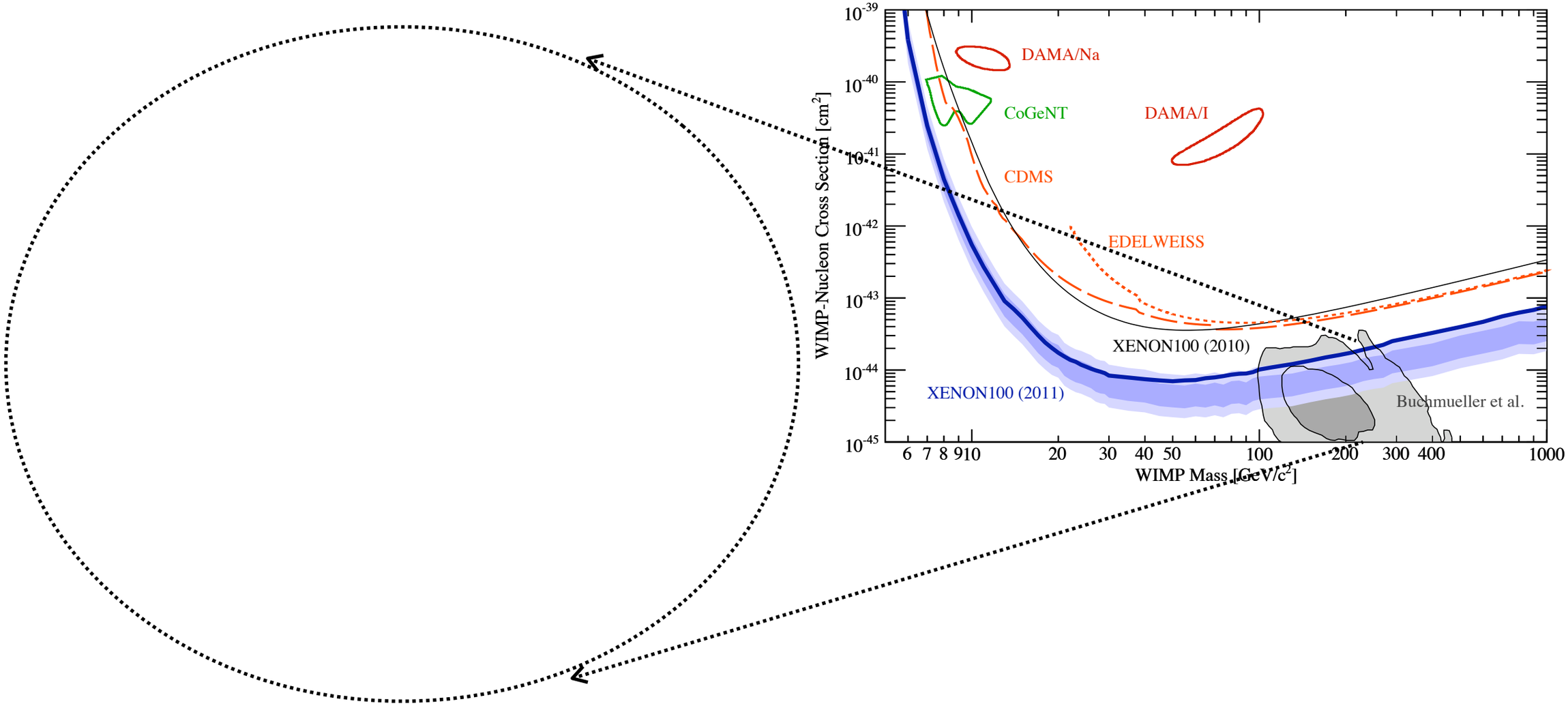

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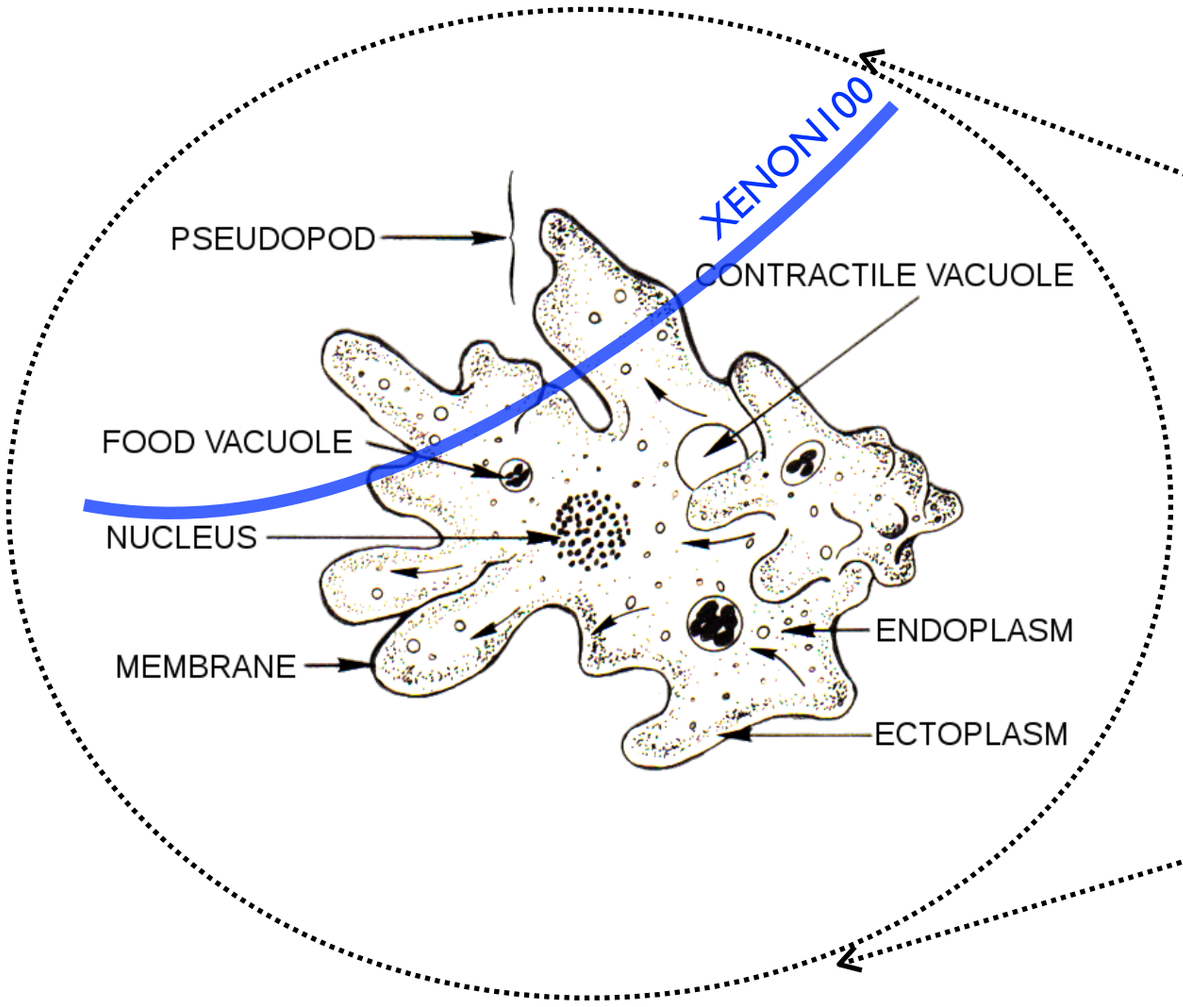

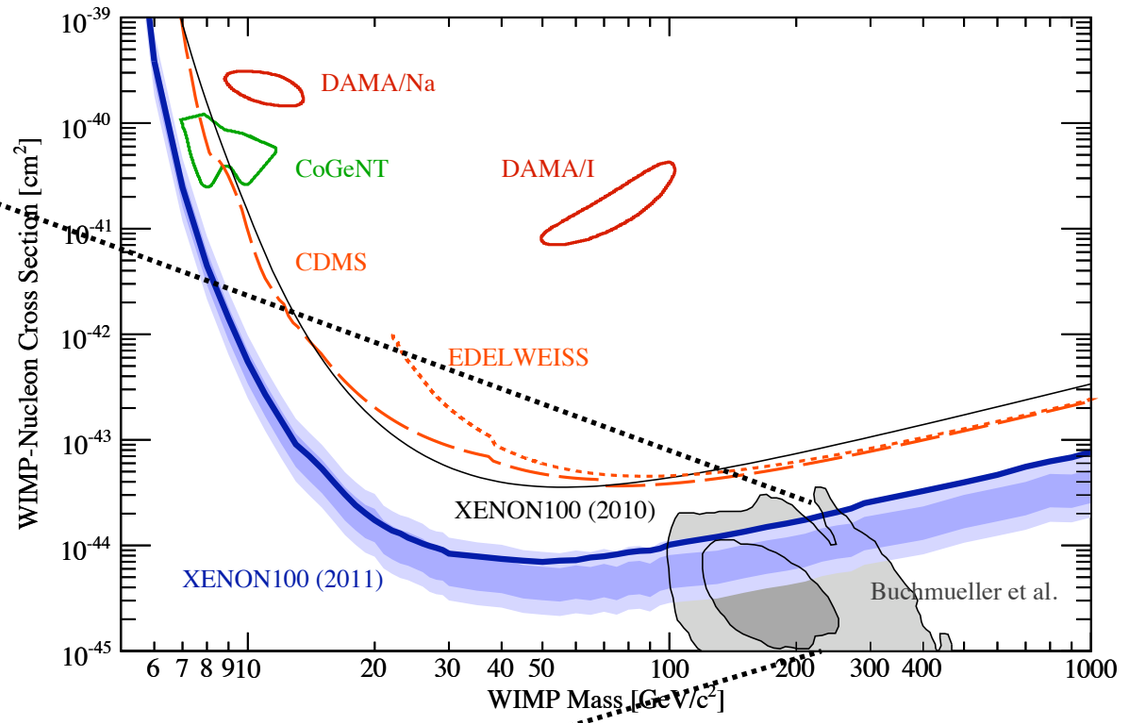

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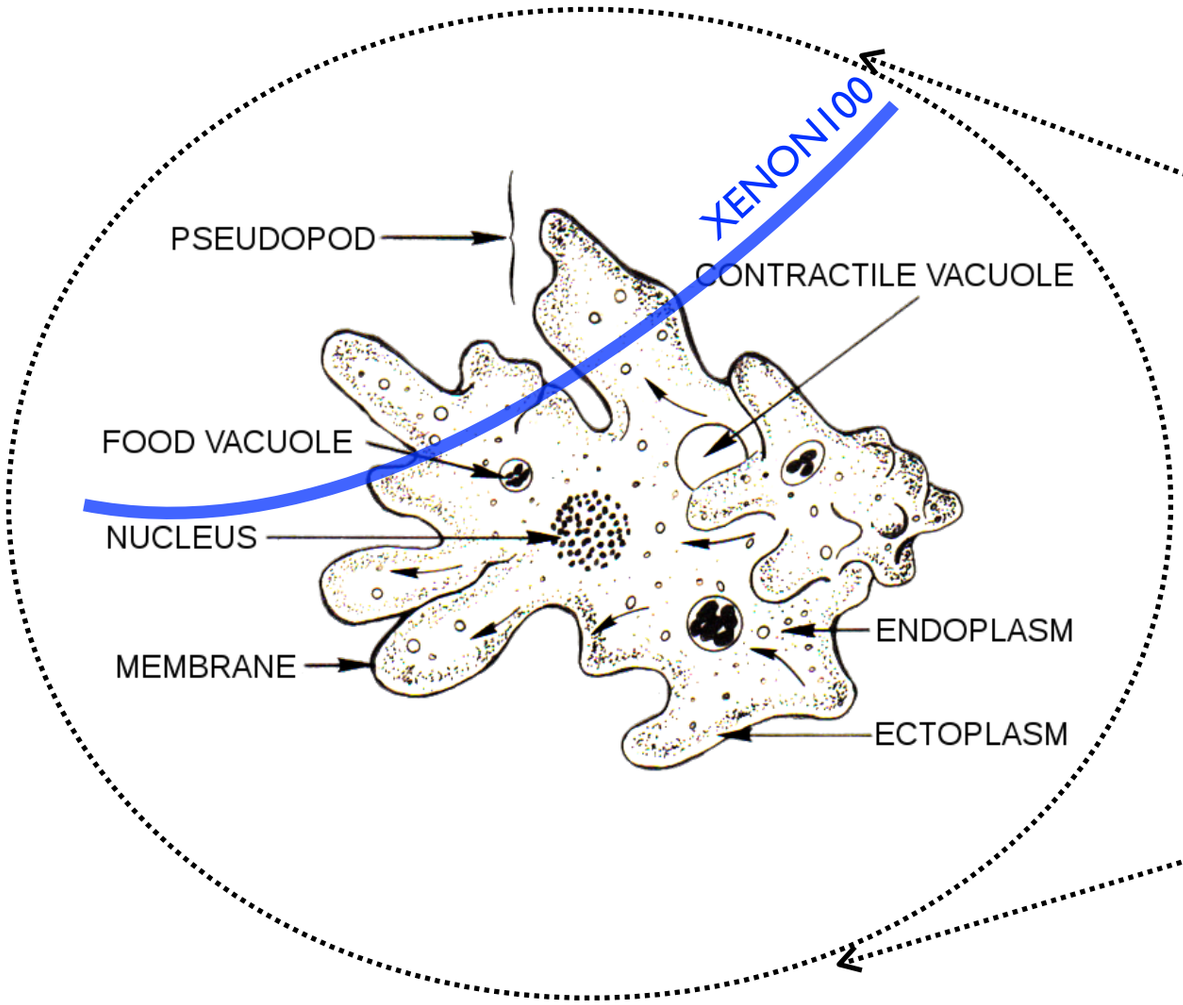

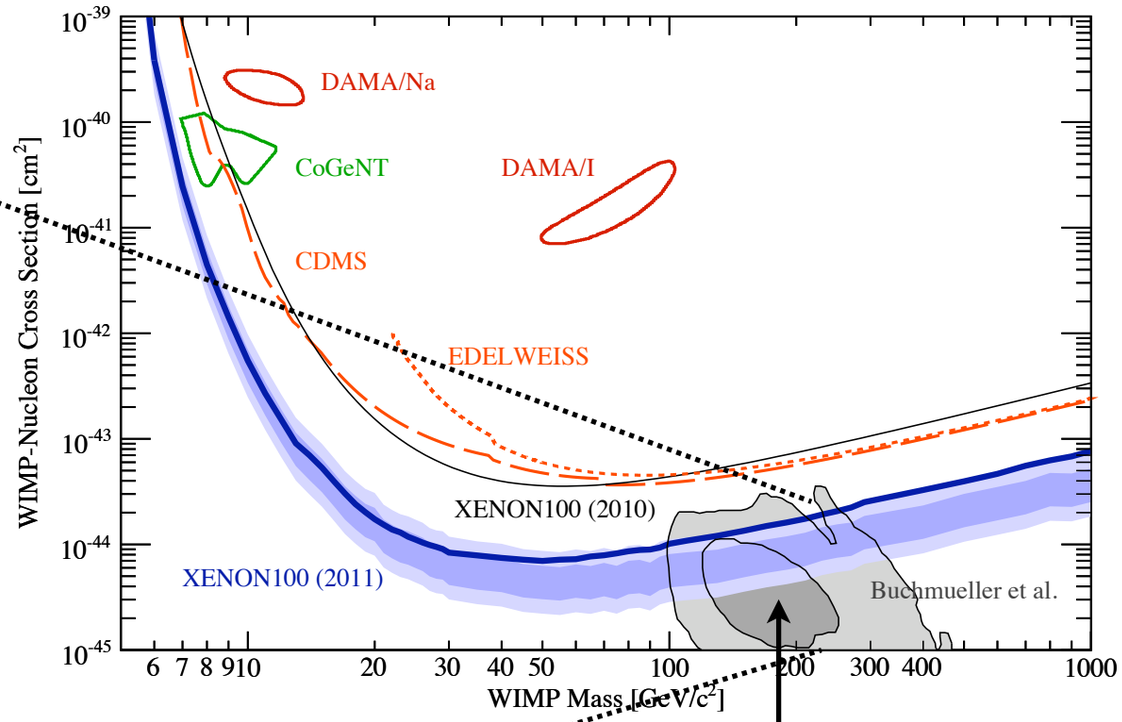

tri-leptons+
jets + MET

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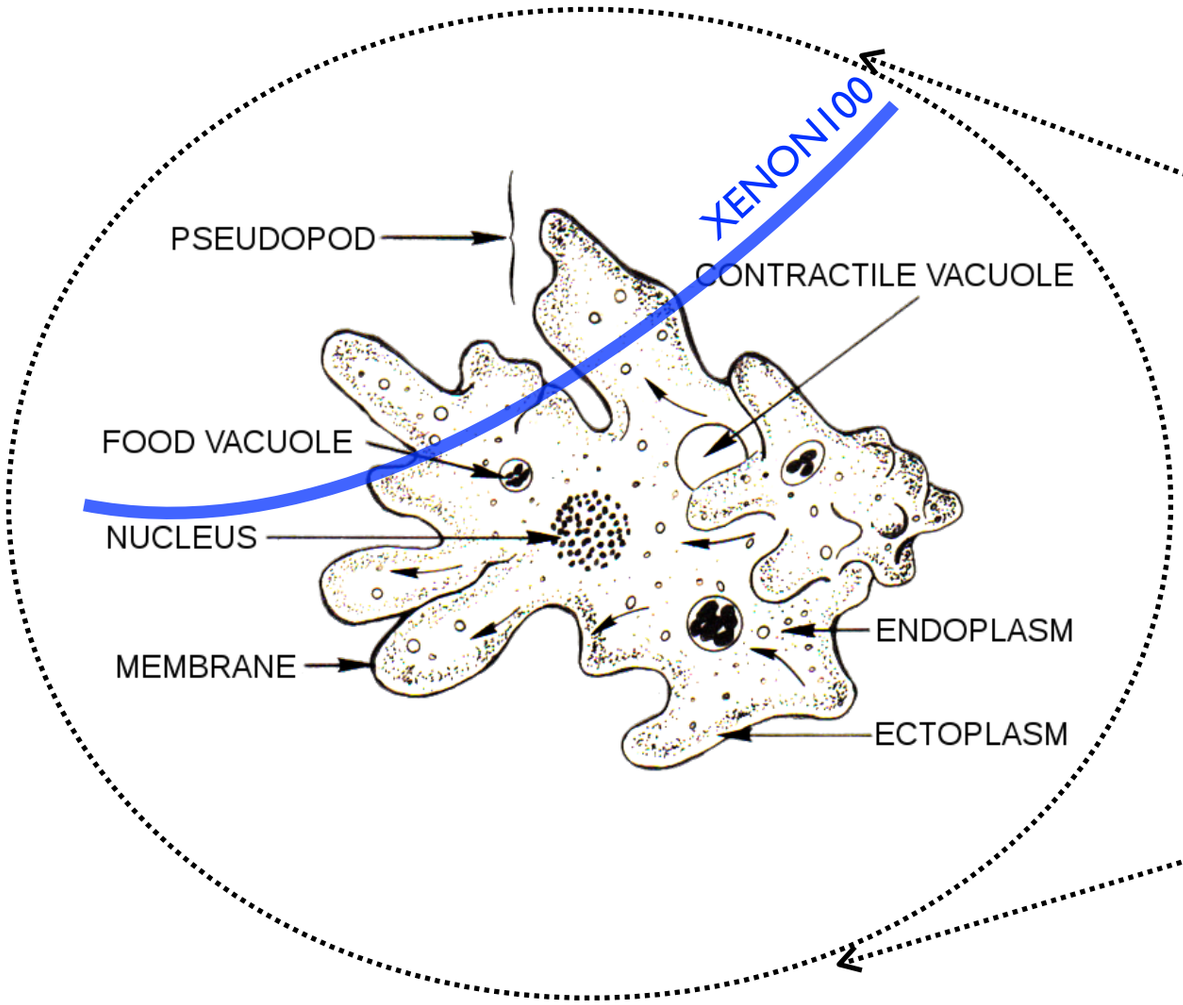

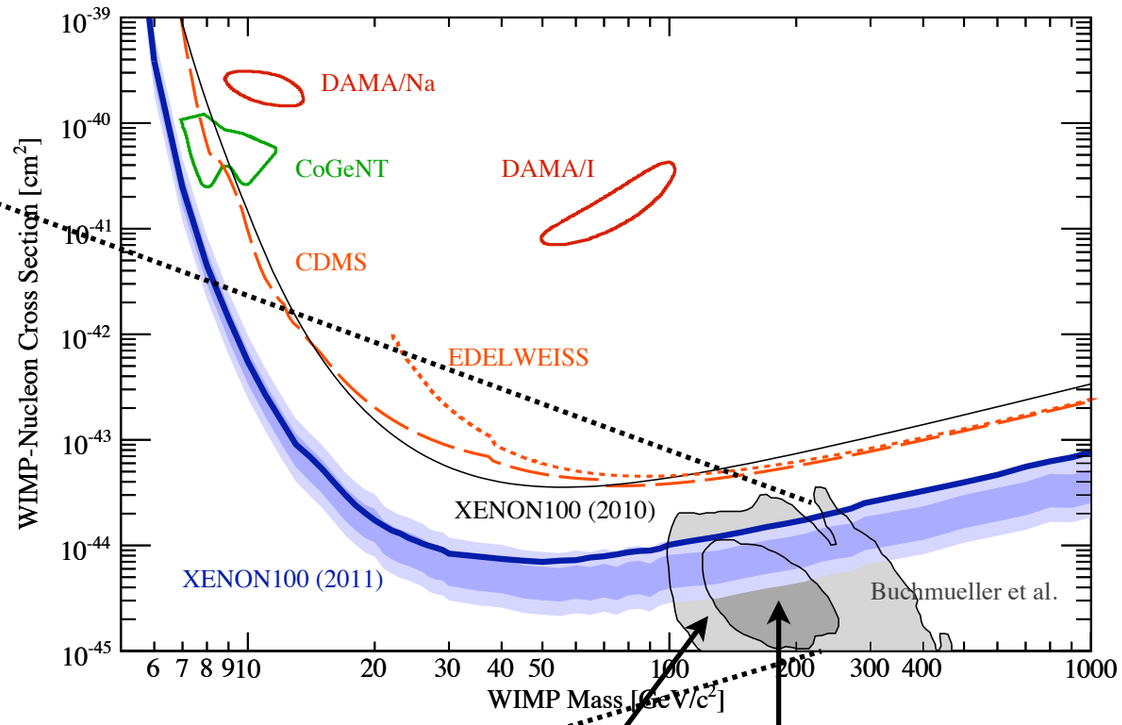

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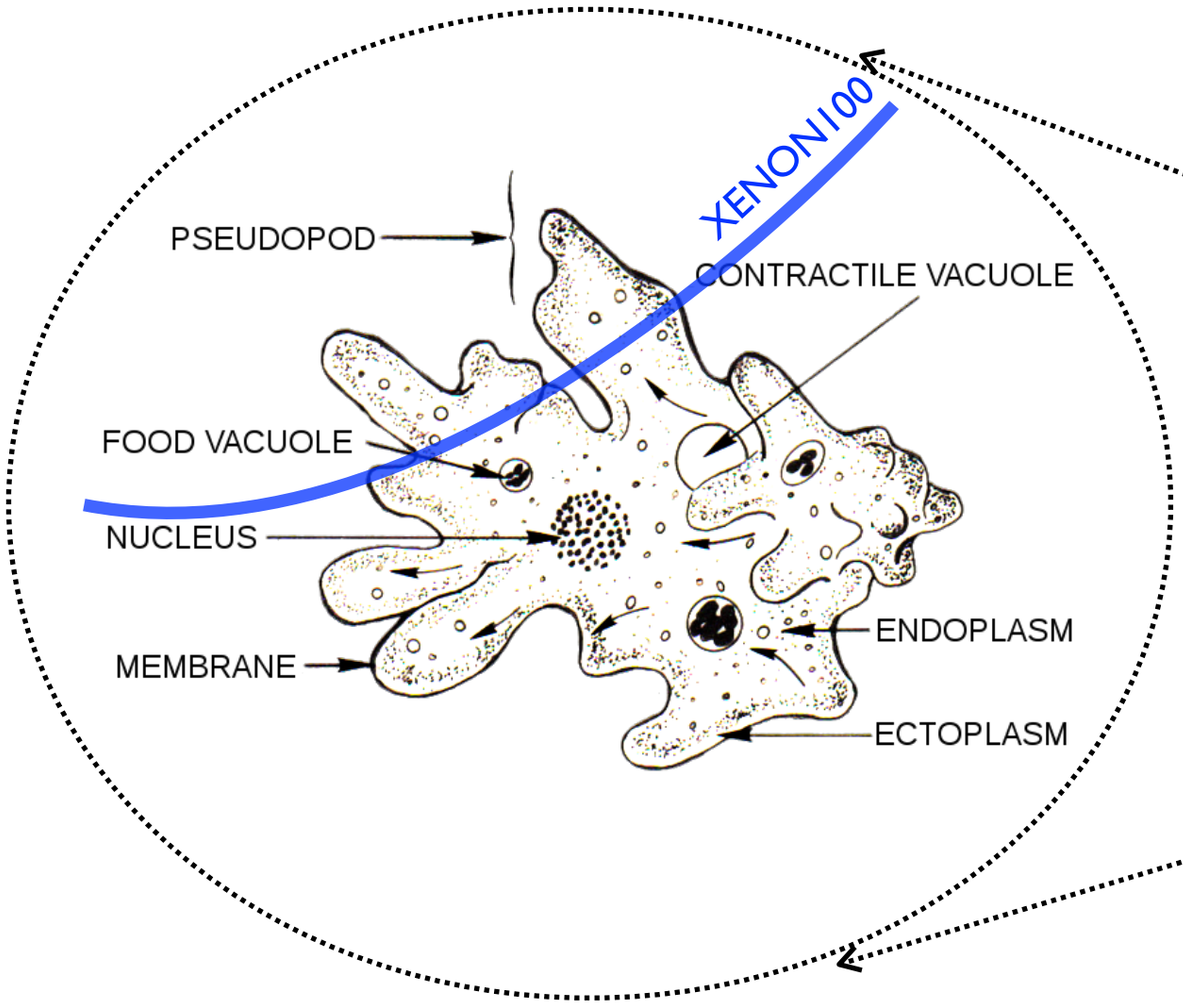

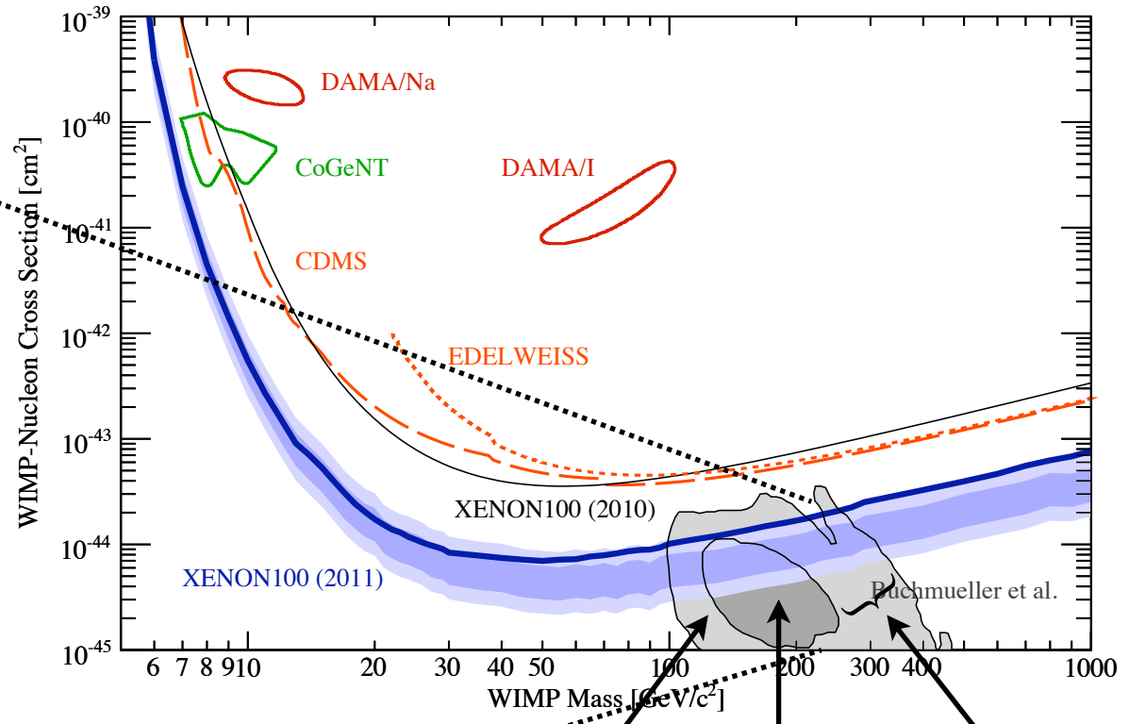

jets + MET

tri-leptons+ jets + MET

same-sign di-leptons +MET

Collider Connections?

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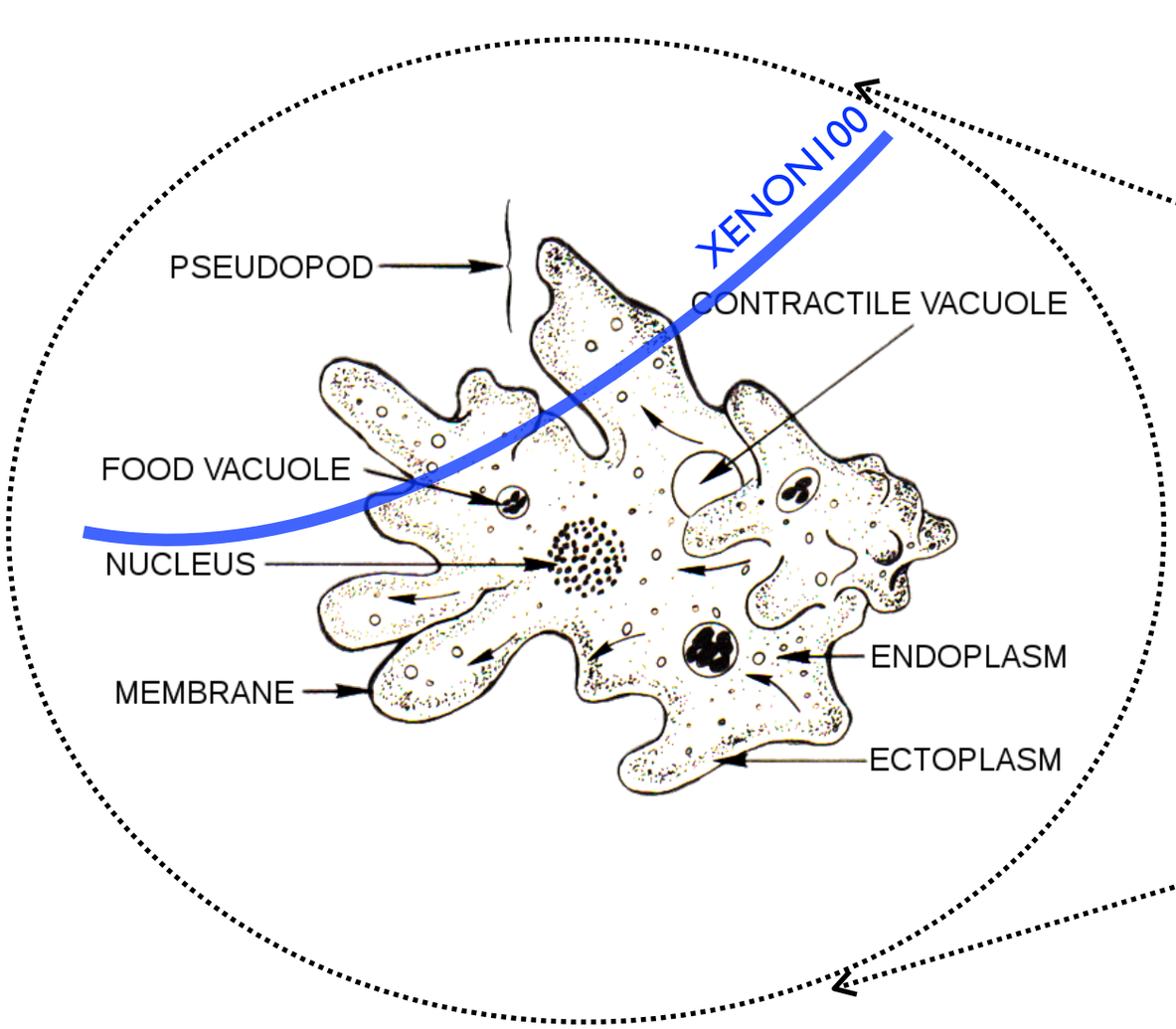

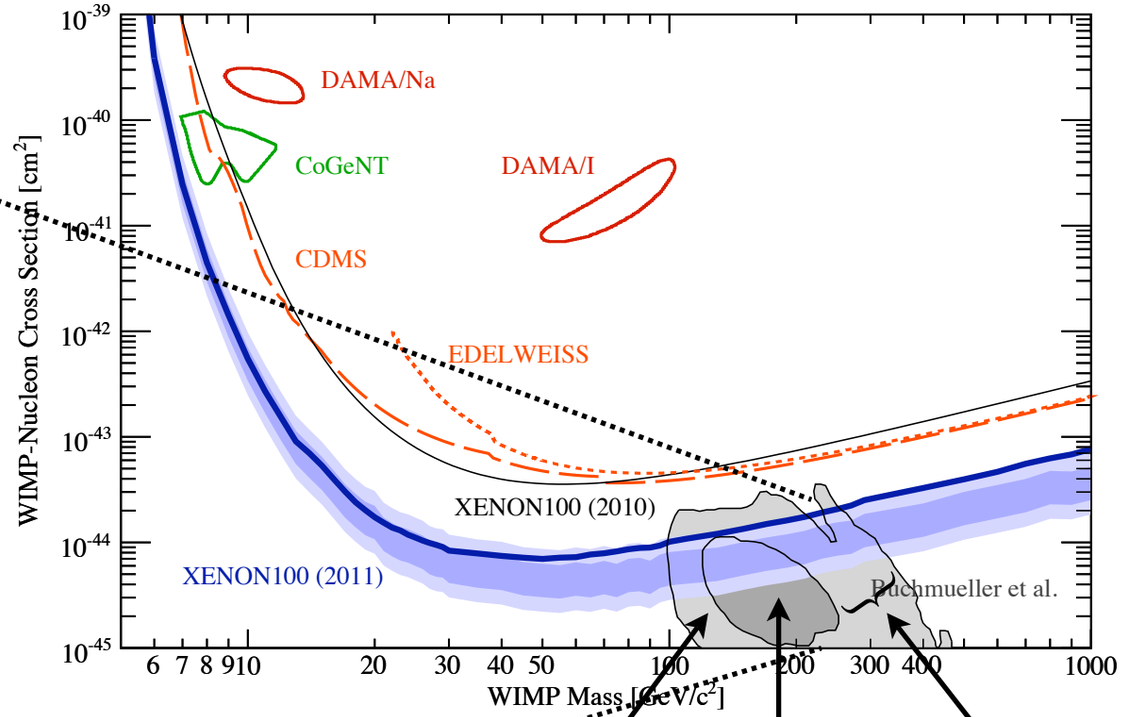

"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [nature **67**, 143 (2011)]